Morphological evidence for geologically young thaw of ice on Mars: a review of recent studies using high-resolution imaging data

Progress in
Physical Geography

Morphological evidence for geologically young thaw of ice on Mars: a review of recent studies using high resolution imaging data

Journal:	*Progress in Physical Geography*
Manuscript ID:	PPG-11-080.R2
Manuscript Type:	Main Article
Keywords:	Mars, Thaw, Periglacial, Geomorphology, Permafrost

Abstract: Liquid water is generally only meta-stable on Mars today; it quickly freezes, evaporates or boils in the cold, dry, thin atmosphere (surface pressure is about 200 times lower than on Earth). Nevertheless, there is morphological evidence that surface water was extensive in more ancient times, including the Noachian Epoch (~ 4.1 Ga to ~ 3.7 Ga bp), when large lakes existed and river-like channel networks were incised, and early in the Hesperian Epoch (~ 3.7 Ga to ~ 2.9 Ga bp), when megafloods carved enormous channels and smaller fluvial networks developed in association with crater-lakes. However, by the Amazonian Epoch (~ 3.0 Ga to present), most surface morphogenesis associated with liquid water had ceased, with long periods of water sequestration as ice in the near-surface and polar regions. However, inferences from observations using imaging data with sub-meter pixel sizes indicate that periglacial landscapes, involving morphogenesis associated with ground-ice and/or surface-ice thaw and liquid flows, has been active within the last few million years. In this paper, three such landform assemblages are described: a high latitude assemblage comprising features interpreted to be sorted clastic stripes, circles and polygons, non-sorted polygonally patterned ground, fluvial gullies, and solifluction lobes; a mid-latitude assemblage comprising gullies, patterned ground, debris-covered glaciers and hill-slope stripes; and an equatorial assemblage of linked basins, patterned ground, possible pingos, and channel-and-scarp features interpreted to be retrogressive thaw-slumps. Hypotheses to explain these observations are explored, including recent climate change, and hydrated minerals in the regolith 'thawing' to form liquid brines at very low temperatures. The use of terrestrial analog field sites is also discussed.

Liquid water is generally only meta-stable on Mars today; it quickly freezes, evaporates or boils in the cold, dry, thin atmosphere (surface pressure is about 200 times lower than on Earth). Nevertheless, there is morphological evidence that surface water was extensive in more ancient times, including the Noachian Epoch (~ 4.1 Ga to ~ 3.7 Ga bp), when large lakes existed and river-like channel networks were incised, and early in the Hesperian Epoch (~ 3.7 Ga to ~ 2.9 Ga bp), when megafloods carved enormous channels and smaller fluvial networks developed in association with crater-lakes. However, by the Amazonian Epoch (~ 3.0 Ga to present), most surface morphogenesis associated with liquid water had ceased, with long periods of water sequestration as ice in the near-surface and polar regions. However, inferences from observations using imaging data with sub-meter pixel sizes indicate that periglacial landscapes, involving morphogenesis associated with ground-ice and/or surface-ice thaw and liquid flows, has been active within the last few million years. In this paper, three such landform assemblages are described: a high latitude assemblage comprising features interpreted to be sorted clastic stripes, circles and polygons, non-sorted polygonally patterned ground, fluvial gullies, and solifluction lobes; a mid-latitude assemblage comprising gullies, patterned ground, debris-covered glaciers and hill-slope stripes; and an equatorial assemblage of linked basins, patterned ground, possible pingos, and channel-and-scarp features interpreted to be retrogressive thaw-slumps. Hypotheses to explain these observations are explored, including recent climate change, and hydrated minerals in the regolith 'thawing' to form liquid brines at very low temperatures. The use of terrestrial analog field sites is also discussed.

Morphological evidence for geologically young thaw of ice on Mars: a review of recent studies using high resolution imaging data

1. Introduction

Data from the most recent Mars missions, such as NASA's *Mars Global Surveyor* (MGS; 1997-2006; Albee et al., 2001) and *Mars Reconnaissance Orbiter* (MRO; 2006 and ongoing; Zurek and Smrekar, 2007) and ESA's *Mars Express* (MEx; 2004 and ongoing; Chicarro et al., 2004), have revealed new evidence for recent geological activity on Mars (e.g., Malin et al., 2006; Marquez et al., 2004; McEwen et al., 2011). In particular, these missions have provided new insights to the geomorphic activity of water and ice on Mars. For example, one of the most significant results from the MGS mission was the observation of kilometre-scale gullies (Malin and Edgett, 2000) that were interpreted to have been created by flows of liquid water. Importantly, these gullies formed only in the last few million years (Reiss et al., 2004), rather than in Mars' more distant past (for a brief summary of Mars' geological timescale, evolution and ongoing research, see Bargery et al., 2011) when large scale hydrogeological activity was more common (Baker, 2001; Carr, 1987). This conclusion is important, for the geologically recent presence of liquid water at the surface both provides important information about the recent climate, and improves the chances that Mars could have supported life in refugia at or near the surface (e.g., Jakosky, 2007) in recent times.

The gullies, indentified in MGS Mars Orbiter Camera (MOC) Narrow Angle images with a spatial resolution of about 2 m per pixel, are generally interpreted as having formed due to thaw of ice or snow (e.g., Balme et al., 2006; Costard et al., 2002; Dickson and Head, 2009; Levy et al., 2009b). Since the end of the MGS mission in 2006, additional morphological indicators of thaw in Mars' recent past have been identified in newer, even higher resolution imaging data. Much of these new data come from the NASA High Resolution Imaging Science Experiment (HiRISE) instrument, aboard the MRO spacecraft, with a spatial resolution of ~ 30 cm per pixel. These data allow surface features to be identified that were either unseen or ambiguous in the MGS images and such observations highlight the rapid pace at which martian geomorphology is advancing.

In this paper, case studies from the literature (either drawn from a single work or as a synthesis of several studies) are presented that utilize these new data, each study documenting an assemblage of landforms interpreted to have formed by thaw of snow and/or ground ice on Mars in the past few million years. The aim of this work is not to review exhaustively the ice related landforms on Mars, but instead to demonstrate the recent progress made (largely due to HiRISE data) in demonstrating that thaw has played a role in shaping the martian surface in the last few million years. In particular,

recent work has suggested that ground-ice thaw might have shaped the surface, in addition to the melt of surface ice or snow proposed to play a major role in shaping or creating gullies (e.g., Levy et al., 2009b). The paper includes first a brief summary of relevant aspects of the martian climate, and a short description of the most common landforms thought to be indicative of near-surface ice (with or without thaw) on Mars. Three landforms assemblages, described in the recent literature as being indicative of thaw, are reviewed. The paper concludes by considering whether thaw on Mars is indicative of recent climate-warming events, or if other explanations, including the local depression of freezing points by the inclusion of salts in regolith materials and fluids, are more likely.

2. Water and the martian climate

Mars' current climate is cold and dry (e.g., Read and Lewis, 2004): the atmosphere is 95% CO_2 (Owen et al., 1977) and the mean annual surface temperature is ~ 210 K, although surface temperatures can range between 140 to 300 K (Kieffer et al., 1977). Atmospheric pressure is below 10 hPa (Hess et al., 1977), with column abundances of water less than 100 precipitable microns, even above the north polar ice cap in summer (Jakosky and Farmer, 1982). Mars' axial obliquity (currently ~26°; Laskar et al., 2004) means that high latitude winter temperatures are so low that CO_2 condenses from the

atmosphere to form a seasonal dry-ice cap that persists well into spring. Thus water on Mars is today stable on multiyear timescales only in the solid state (liquid water can persist briefly on Mars, even today, as discussed by Hecht, 2002) and even then only in the coolest regions, such as steep, pole facing slopes at latitudes higher than about 25° or in almost all terrains at latitudes higher than about 60° (Aharonson and Schorghofer, 2007; Schorghofer and Aharonson, 2005).

There is, however, strong morphological evidence that surface water was more extensive in Mars' ancient Noachian (~ 4.1 Ga to ~ 3.7 Ga bp) and Hesperian (~ 3.7 Ga to ~ 2.9 Ga bp) epochs than today, including valley networks, outflow channels and palaeolakes (e.g., Ansan and Mangold, 2006; Baker, 2001; Carr, 1987; Irwin et al., 2005; Mangold et al., 2004). Such observations have been interpreted as evidence for an early warmer, wetter martian climate, in which liquid water was more stable (e.g., Craddock and Howard, 2002) although these interpretations are still widely debated and it is not known whether Mars was actually 'warm and wet' or instead was 'cold and wet' (e.g., Fairen, 2010; Fastook et al., 2012). Since the onset of the Amazonian Epoch (~ 3.0 Ga to present), Mars' has been colder and dryer, and most of Mars' water is thought to have been locked away as ice in the regolith, forming an extensive cryosphere buried beneath dryer material (Carr, 2000) or exposed at the poles, although large-scale volcanic, tectonic and fluvial events could have caused significant climate

excursions in the past by releasing large amounts of volatiles into the atmosphere (e.g., Baker et al., 1991).

Although the Amazonian is probably the driest and coldest of Martian epochs, there have been climate changes within the epoch relevant to the behaviour of water and ice. This is because unlike the Earth, Mars has no large moon to stabilise its rotation, so the martian axial obliquity has varied ~ 15° and 35° in cycles lasting ~ 120,000 years (see Figure 2, after Laskar et al., 2004). Furthermore, modelling has shown that Mars' mean obliquity changed from about 35° to about 25° about five million years ago (Laskar et al., 2004), perhaps defining a recent period in which insolation patterns have been atypical and which might have associated geomorphological consequences (e.g., Head et al., 2008), or even defining martian 'ice-ages' (Head et al., 2003). Hence we define "recent" in this paper as meaning the last ~ 20 ma, the period over which Mars' obliquity and eccentricity can be precisely modelled (Laskar et al., 2004), and during which there were both many obliquity cycles, and the systematic change in the mean obliquity about 5 ma ago.

Can the formation of different types of landforms and landscapes be associated with such recent changes in past climate? When trying to answer this question, it must be noted that the main way to determine *when* martian surfaces were formed is to examine

the size-frequency statistics of impact craters superposing them (e.g., Hartmann and Neukum, 2001). Small and geologically recent features have few superposed impact craters, and so are difficult to date in absolute terms (Hartmann, 2007). Major uncertainties associated with craters smaller than 200 m are the effects of target properties (e.g., Dundas et al., 2010a) and the possible contamination by secondary craters (e.g., McEwen and Bierhaus, 2006). The accuracy of crater retention ages obtained for small features might never be better than an order of magnitude (Hartmann, 2007), although this is good enough for many studies.

Furthermore, landforms on Mars need not have formed under the present day climate to appear youthful but could be significantly older because, compared with the Earth, the rate of erosion and burial is extremely low. Estimates of erosion rates on Mars show a rapid decrease from 10^{-7}–10^{-5} myr^{-1} in Noachian terrains (characterized by rimless, flat-floored craters and valley networks) to the exceedingly slow rates of 10^{-11} to 10^{-10} myr^{-1} during the Hesperian and Amazonian periods (Golombek and Bridges, 2000). These recent values are many orders of magnitude lower than terrestrial continental denudation rates. Hence, martian surfaces that are millions of years old can appear pristine. This is particularly important to consider when trying to link landforms and landscape thought to have formed by thaw to the cyclic changes in Mars' orbital parameters over the past few million years (Kreslavsky et al., 2008). Consequently it

might be difficult to differentiate from morphology alone between landforms decades or centuries old, formed under present day conditions, and those created during different obliquity and eccentricity (and perhaps climate) conditions, hundreds of thousands (or even millions) of years ago.

3. Components of thaw-related martian landscapes

Much of the landscape of the northern plains of Mars, seen in Viking Orbiter images, was ascribed to 'periglacial' modification based on their "grooved, mottled, knobby and ridged morphologies" (Tanaka et al., 1992) and on the identification of apparent thermokarst (e.g., Carr and Schaber, 1977; Costard and Kargel, 1995) and polygonally patterned grounds in the highest resolution (up to 7.5m per pixel; Snyder and Moroz, 1992) Viking images (Lucchitta, 1981). It should be noted that the term 'periglacial' is sometimes poorly defined in planetary science. We define 'periglacial' as *landforms or landscapes shaped by transitory ice, generally inferring processes of freeze-thaw with a seasonal or otherwise cyclical oscillation of water between a solid (frozen) and liquid state*. The ages of 'periglacial' terrains seen in Viking images were poorly constrained (Carr and Schaber, 1977; Lucchitta, 1981; Rossbacher and Judson, 1981) and the evidence for thaw in the landscape was ambiguous. Newer studies using modern datasets with higher spatial resolution (e.g. from HiRISE and MOC) have identified a variety of possibly thaw-related landscapes, and it has been inferred that many are

geologically recent. The landforms that most often compose such landscapes, including both periglacial landforms in the strict sense and other landforms related to ice and thaw of ice that are found in association with them, are described below. Table 1 summarises these components and Figure 3 shows examples of landforms in which liquid water derived from thaw or snowmelt is thought to have played a formative role.

3.1 Polygonally patterned ground

Polygonised ground is widespread on Mars. While polygons might be the result of desiccation (El Maarry et al., 2010) and other processes such as tectonic uplift, rock jointing, or convection in a lava lake (for a comprehensive overview of proposed mechanisms see the appendix and cited references in Levy et al., 2009a), many small-scale polygons with diameters of meters to tens of meters are closely analogous to terrestrial thermal contraction polygons based on several comparative criteria (Mellon, 1997). Furthermore, their distribution is strongly latitude-dependent (Levy et al., 2009a; Mangold, 2005; Seibert and Kargel, 2001), implying a control by climatic or global environmental factors. Levy et al. (2010) compared polygons on Mars with terrestrial analogues in Arctic and Antarctic environments, examining polygon plan-form morphology, microtopography, sediment sorting patterns, landform ages, and relationships between polygons and other landforms (e.g., gullies, desert pavements,

boulder halos). They concluded that martian polygons are probably sand wedge or sublimation polygons, rather than ice-wedge polygons. This conclusion is not supportive of the concept of freeze/thaw cycles as factors in recent Martian geomorphology. However, making a distinction between different types of thermal contraction polygons on the basis of remote-sensing and in situ imagery and derived topographic information alone is problematic on Earth, and more so on Mars (Ulrich et al., 2011).

3.2 Sorted patterned ground (stripes, circles and lobate forms)

Possible spatial sorting of regolith into fine and coarse particle size domains on martian mid-latitude crater walls has been observed by Hauber et al. (2011a) and Mangold (2005), where alternating stripes of bright and dark albedo surfaces are oriented down slope. Stronger evidence for sorted landforms comes from observations where clasts can be resolved: clastic stripes, circles and labyrinths at high latitude are described by Gallagher et al. (2011) and Gallagher and Balme (2011). Sorted circles and polygons have also been found at the margins of what appear to be fluvial flood-carved channels near the equator (Balme et al., 2009). In addition to sorted stripes and circles, distinctive clastic and non-clastic lobes have been found on the same impact crater walls (Gallagher and Balme, 2011; Gallagher et al., 2011; Johnsson et al., 2011), as shown in

Figure 3. Together, these observations are consistent with an origin by a combination of cryoturbation, frost creep, solifluction, sorting and gravitational slumping.

Simple clastic patterns might occur without the presence of water, through gravitational slumping of clasts into thermal contraction cracks (e.g., Levy et al., 2009a; Mellon, 1997), and sorting driven by seasonal deposition of CO_2 frost 'locking' boulders in place while the ground contracts beneath has also been proposed (Orloff et al., 2012). However, such mechanisms arguably explain neither the full variety nor the spatial associations of sorted morphologies observed as comprehensively as does a genesis involving freeze-thaw processes.

3.3 Viscous flow features

Viscous flow features, widespread on Mars, are a family of landforms usually tens of kilometres in scale that were originally identified in Mariner and Viking images (e.g., Squyres, 1979) and include features descriptively termed lobate debris aprons, lineated valley fill, and concentric crater fill. Such features are not periglacial, but are instead probably glacial, so they are not in themselves indicators of thaw. Their distribution is confined to mid-latitudes (Milliken et al., 2003; Squyres and Carr, 1986) but relict forms (Hauber et al., 2008) and some crater-floor morphologies (Shean, 2010) indicate

a former extent towards latitudes lower than 30°. Their morphology was interpreted as indicative of plastic deformation, and they were originally interpreted as rock glaciers (Squyres, 1979). However, morphologic analysis (Hauber et al., 2008) and radar measurements (Holt et al., 2008; Plaut et al., 2009) suggest that they consist of relatively pure ice overlain by a protecting surface lag, hence debris-covered glacier is a more appropriate term to describe them.

Higher resolution images show a preferential occurrence of smaller-scale (km) viscous flow features (referred to as Glacier-like forms (GLFs) by Hubbard et al., 2011) on pole-facing mid-latitude slopes of any type of relief (Milliken et al., 2003; Souness et al., 2012). Their morphology, too, suggests plastic or superplastic deformation (Li et al., 2005; Milliken et al., 2003), and so they also have been interpreted as debris-covered glaciers (Head et al., 2010) or 'dust glaciers' (Hauber et al., 2011a). We use the term debris-covered glaciers for these features, albeit following the rather generic definition of rock glaciers as of Berthling (2011: , p. 105), who suggested that rock glaciers are 'the visible expression of cumulative deformation by long-term creep of ice/debris mixtures under permafrost conditions'. In this context, ice could have been incorporated in talus or dust from seasonal frost (Squyres, 1979) or by the direct incorporation of ground ice (Lucchitta, 1984).

3.4 Small-scale Valleys

While the ubiquitous creep of the ice-rich permafrost material on Mars does not require liquid water to occur, some kilometre-scale fluviatile valleys seem to be closely associated with debris-covered glaciers (Dickson et al., 2009; Fassett et al., 2010; Howard and Moore, 2011), being proglacial (a term usually formally applied to glacial environments, but fitting the context of debris-covered glaciers as defined above), situated down slope of the debris-covered glaciers, or supraglacial (i.e. incised on the surfaces of the debris-covered glaciers). Consequently, it is reasonable to hypothesize that these are glaciofluvial valleys. Although they date to the Amazonian Epoch and are not 'recent' as defined in this review, these valleys attest to limited melting of the ice contained in the debris-covered glaciers (Dickson et al., 2009; Fassett et al., 2010; Howard and Moore, 2011) and are a part of a mid-latitude ice-related landscape assemblage described below.

3.5 Pitted and scalloped terrains

Scalloped depressions in mid-latitude regions (such as Utopia Planitia and Malea Planum) display asymmetric cross sections in a north-south orientation, with pole-facing scarps being steeper than equator-facing scarps. The depressions, which are

overprinted by polygonal patterns, are thought to be the result of the degradation of an ice-rich mantling deposit (e.g., Costard and Kargel, 1995; Lefort et al., 2009; Morgenstern et al., 2007; Zanetti et al., 2010). Although some studies suggested the presence of Amazonian-age thaw lakes inside the depressions (Costard and Kargel, 1995; Soare et al., 2007; Soare et al., 2008), the evidence for morphogenesis involving liquid water is ambiguous. The observed morphology can also be explained by dry degradation via sublimation (Séjourné et al., 2011; Ulrich et al., 2010). Numerical models of landform topographic profile development involving sublimation generate morphologies indistinguishable from profiles of actual topography rendered in HiRISE Digital Elevation Models (Lefort et al., 2009).

3.6 Pitted and fractured mounds

Some fractured mounds on Mars morphologically resemble terrestrial pingos. They occur both on plains such as Utopia Planitia and on the floors of impact craters and some recent (a few tens of million years at most; Burr et al., 2002b) flood-carved channels. Despite their morphological similarity, an origin as pingos is debatable. Other processes can result in similar morphologies (e.g., pseudocraters; Burr et al., 2009; Lanagan et al., 2001), and the mounds could also be erosional remnants of an ice-rich mantling (Dundas and McEwen, 2010; Hauber et al., 2011a). Mounds in Utopia

Planitia, however, might have formed as hydrostatic (closed-system) pingos on the floors of possible thermokarst depressions, analogous to hydrostatic pingos on the floor of drained thaw lakes on Earth (Burr et al., 2009). Alternatively, an origin of some crater floor-mounds as hydraulic (open-system) pingos could also be envisaged. In this scenario liquid water would be provided by basal melting of glaciers on the crater walls. The water would then infiltrate the permafrost-free substrate beneath the glacier and move downward and towards the crater floor, where it could build up artesian pressure under the permafrost seal on the non-glaciated crater floor (Hauber et al., 2011a). Basal melting on post-Noachian Mars would, however, require anomalously high heat flows (Russell and Head, 2007) and it is highly unlikely that it would occur under recent Martian environmental conditions (Fastook et al., 2012).

3.7 Gullies

Mid-latitude martian slopes are typically dissected by erosional features that resemble ravines on Earth. As shown in Figure 3, they display a tripartite morphology, consisting of an erosional alcove, one or several channels, and a depositional apron (Malin and Edgett, 2000). The total lengths of these systems are commonly a few kilometres (Balme et al., 2006). Despite these considerable dimensions, they were termed gullies when first described in detail by Malin and Edgett (2000). Repeat observations revealed

current activity on some gullies (Diniega et al., 2010; Dundas et al., 2010b; Reiss et al., 2010). Some of the changes, in particular the formation at two locations of bright deposits without apparent topographical changes (Malin et al., 2006) could be attributed to dry landsliding (Pelletier et al., 2008). Although several formational mechanisms were proposed, including flow suspended by liquid CO_2 (Musselwhite et al., 2001), dry granular flows (Treiman, 2003; Bart, 2007), and downwasting of accumulated CO_2 frost (Dundas et al., 2010b), there is a growing consensus that the overall morphology of gullies is best explained by processes involving liquid water, i.e. fluvial runoff or debris flows (e.g., Conway et al., 2011a; Mangold et al., 2010; Reiss et al., 2011). The gullies were originally suggested to have formed from seeps emerging from underground sources (Malin and Edgett, 2000), but the likely source of water is now thought to be melting of snow or near-surface ice (e.g., Williams et al., 2009; Balme et al., 2006; Costard et al., 2002; Dickson and Head, 2009; Levy et al., 2009b; Möhlmann, 2010).

3.8 Recurring slope lineae:

Repeat HiRISE images of southern hemisphere martian craters show the ongoing seasonal occurrence of dark slope lineae on some mid-latitude slopes in Mars' southern hemisphere (Figure 3; McEwen et al., 2011). These lineae recur in southern spring and summer predominantly on equator-facing scarps, where peak summer temperatures can

reach 250-300 K. Although several hypotheses regarding the origin of the slope lineae are discussed by McEwen et al. (2011), their favoured interpretation is the down slope transport of a salt-bearing, water-based liquid (e.g., a 'cryobrine' with a lowered freezing point; Möhlmann and Thomsen, 2011) that darkens the surface of the recurrent slope lineae through grain-wetting, and that then sublimates/evaporates once flow ceases after the summer thermal optimum. This mechanism is consistent with modelling of groundwater flow in sandy, unconsolidated regolith and is analogous to the formation of water tracks on slopes in Antarctica (Levy, 2012).

4. Landscapes on Mars indicative of thaw

Although all the landforms shown in table 1 probably formed in association with water-ice, not all require liquid water. Possibly the strongest evidence for liquid water from a single landform type comes from fluvial-like gullies (e.g., Conway et al., 2011a; Reiss et al., 2011). Nevertheless, inferring formative environments and processes from observations of individual landforms can be difficult, even on Earth and is more challenging on Mars, where the availability of in-situ field data of any kind is the exception, rather than the norm. Hence while synoptic studies of individual landforms such as gullies (e.g., Balme et al., 2006; Dickson et al., 2007), polygons (e.g., Levy et al., 2009a; Mangold, 2005) or glacial-like-forms (Souness et al., 2012) are important,

inferring process from form is challenging. Considering suites of landforms, and the relationships between the individual elements, provides an alternative means of testing hypotheses about morphogenesis. Hypotheses can be further tested by considering whether on Mars the spatial and topographical distributions of a suite of landforms within the landscape follow similar patterns to analogous landscapes on Earth (e.g., Balme and Gallagher, 2009; Levy et al., 2009b; Marchant and Head, 2007; Hauber et al., 2011a). In the following sections, therefore,, we review three key landform assemblages and the rationale used in the recent literature to infer component and assemblage morphogenesis and environmental context, especially the spatially and temporally varying geomorphic role of thaw liquids, on Mars in the recent past.. These assemblages are dealt with here on a latitudinal basis to organise the literature but also to emphasise the complex relationship between climate and landscape inheritance, for example of topography, materials and volatiles, in morphogenesis.

4.1. Mid-latitude assemblage

The mid-latitude regions of Mars, defined here as the areas between roughly 30° and 60° in both hemispheres, are particularly interesting for investigations of periglacial processes for two main reasons. First, they represent an area of transition between the high latitudes, which are characterized by a high amount of very near-surface ground ice

(e.g. Feldman et al., 2004), and the presently ice-free equatorial regions. Second, the mid-latitudes display a variety of landforms that are morphologically analogous to terrestrial periglacial surface features (e.g., Hauber et al., 2011b). Moreover, the distribution of many of these landforms is confined to the mid-latitudes, implying a climatic control. The mid-latitudes are also a region where ice is available as a prerequisite for melting, even if melting of such ice is probably a rare event (Costard et al., 2002; Hecht, 2002). Repeat remote sensing of fresh impact craters revealed that ground ice is present very close to the surface (Byrne et al., 2009), a view that was confirmed by spectral measurements showing evidence for water ice beneath CO_2 frost and an ice-free, rocky surface lag (Vincendon et al., 2010). Indeed, seasonal ice accumulation is an ongoing process in the mid-latitude regions, as repeat images demonstrate (Figure 4).

In the martian mid-latitudes there are at least two landscape types that host possibly periglacial features and which have morphological analogues on Earth. The first such landscape consists of plains without large-scale relief characterized by scalloped depressions that cut large polygons. In turn, the scalloped depressions are cross-cut by smaller polygons. Small mounds can be observed on the floors of some scalloped depressions and small craters. The northern parts of Utopia Planitia, in Mars' northern hemisphere provide a good example of this type of landscape. On Earth, similar

landform assemblages form in periglacial environments, the polygons being ice- or sand-wedge types, the depressions reflecting degradation of an ice-rich substrate and the mounds being hydrostatic (closed-system) pingos. Such landform assemblages are found in arctic lowland areas on Earth, e.g., in northern Siberia, which has been studied as a morphological analogue to Utopia Planitia on Mars (Ulrich et al., 2010). While the morphological evidence for ice in the near-surface is strong in this assemblage (Lefort et al., 2009; Morgenstern et al., 2007; Séjourné et al., 2011; Soare et al., 2005; Ulrich et al., 2011), the evidence for thaw is equivocal, for it is difficult to determine whether the scalloped depression formed by sublimation or melting.

The second broad type of periglacial landscape in the martian mid-latitudes is associated with large-scale topographic features such as impact craters, which provide considerable relief in both the heavily cratered southern highlands and the low-lying northern plains. Many craters host a series of landforms that could have a periglacial origin, including patterned grounds which are interpretable as possible ice-, sand-, or sublimation polygons, slope stripes, lobate landforms interpreted as debris-covered glaciers, gullies and slope lineae, and mound structures that are similar in shape and morphology to pingos. A morphologically analogous landscape is observed on Svalbard (Hauber et al., 2011b) where elements of both mountain (alpine) and lowland permafrost are present. The mountain massifs in Svalbard display slopes which are characterized by a variety of

sorting and permafrost creep processes (gelifluction, rock glaciers) as well as gullies and debris-flow fans, while the floors of valleys exhibit widespread ice-wedge polygons and many hydraulic (open-system) pingos.

An impact crater in the martian southern highlands (Fig. 6) provides an example of an assemblage that is indicative of thaw, rather than just ice. The interior pole-facing crater wall displays gullies, stripes, and creep features. The gullies and associated fans are indicative of formation by fluvial and/or debris flow processes, both involving liquid water. If the stripes formed by cryoturbation, their presence might indicate freeze/thaw cycles. The slow creep of ice-rich permafrost material might have generated the lobate features, but is not itself indicative of thaw.

A series of tentative scenarios that might explain the landform assemblages in mid-latitude martian craters was suggested by Hauber et al. (2011a), ranging from prevailing 'wet' processes (ice-wedge polygons, pingos) to a dominance of dry processes. Importantly, however, all scenarios require at least some liquid water to explain the occurrence of countless gullies on the inner and outer crater walls and the small fluvial valleys down slope of the lobate (putative debris-covered glacier) features interpreted as permafrost-related landforms.

4.2 High-latitude assemblage

There is extremely strong evidence from gamma ray and neutron spectroscopy that the uppermost parts of the martian regolith at mid- to high-latitudes (ca. 60°N-75°N) contain up to tens of weight-percents of water-ice (e.g., Boynton et al., 2002; Feldman et al., 2004; Feldman et al., 2007). The evidence for liquid water in the mid-latitude assemblage comes mainly from gullies and their association with other ice-related landforms. At high latitudes, the evidence for water comes both from gullies and from a variety of apparently sorted clastic landforms and their associations with one another and the local topography. Martian periglacial sorted stripes and solifluction lobes were inferred from MOC images by Mangold (2005) and in HiRISE images by Hauber et al. (2011a), but in neither case could clasts be resolved. In contrast, Gallagher et al. (2011) showed that slopes of many northern high-latitude impact craters of the order of 1-10 km diameter (e.g., Heimdal Crater near NASA's Phoenix Lander) are patterned by clastic stripes, polygons, circles (Figure 7), possible solifluction lobes and terraces (Figure 3d and Figure 8). What appear to be competent clasts, including ploughing boulders (Johnsson et al., 2012) rather than puzzle rocks (Marchant and Head, 2007), can be resolved in many of these features,. The landforms show a latitude-dependent spatial distribution (Johnsson et al., 2011) and size-frequency statistics of superposed impact craters (Gallagher et al., 2011) demonstrate that the crater retention age of the

surface is less than a few million years, and possibly even less than a few hundred thousand years. On Earth, thaw is inherent to the sorting processes that create periglacial assemblages like these, so thaw must also be considered as a possible process for such landscapes on Mars. However, it should also be noted that there are many more non-sorted polygonal fracture networks visible in these regions that could be interpreted either as dry sand-wedge or sublimation-type polygons, and are probably not indicative of wetter, ice-wedge polygons.

The textural distribution of clasts within the landforms and the morphology of the landforms themselves is consistent throughout the region (Gallagher et al., 2011) and accords with topographical context. For example, on Heimdal crater's rim, where impact-exposed bedrock is closest to the surface, debris is largest and most abundant (Figure 8). Exposed bedrock is relatively absent on the gentler outer crater walls and available clasts tend to be smaller than in crater interiors (Figure 7b). Further from the crater, sorted landforms are minimal and clasts even finer (Figure 7d), indicating that it is possible that active layers are not present on low-slope surfaces (consistent with the model of Kreslavsky, 2008). Clastic stripes occur on steeper slopes, more circular or polygonal forms on less steep slopes (Figure 7), in agreement with terrestrial experience (e.g., French, 2007) and formation models (e.g., Kessler and Werner, 2003). Throughout the latitudinal zone of 60-75° N, the morphology of sorted forms associated with impact

craters is independent of background polygonal fracture networks that are also present here. Clasts are not concentrated within the fractures and some pristine fractures dissect clastic lobes, indicating that some fracturing post-dates sorting (Gallagher et al., 2011; Johnsson et al., 2012). Consequently, the systematic variation in landform morphology with slope and clast availability, and the cross-cutting relationship between fractures and sorted forms are not well explained by mechanisms relying on thermal contraction alone and not involving thaw and solifluction (e.g., Levy et al., 2008; Mellon et al., 2008).

The martian sorted clastic lobes are close morphological analogues of known solifluction lobes in Svalbard (Figure 2) and other terrestrial periglacial environments, with morphometric characteristics indicative of an origin involving thaw-generated solifluction rather than simply creep (Johnsson et al., 2011). For example, they are: planimetrically and dimensionally accordant; both populations originate at slope crests (Johnsson et al., 2012) or follow consecutively down slope from sorted clastic stripes at slope crests; down slope, the clasts in consecutive lobe chains become texturally finer (Ballantyne and Harris, 1994; Gallagher et al., 2011); both populations of lobes are characterised by arcuate, clast-banked overlapping risers (Johnsson et al., 2012).

Ground ice has been directly observed at the Mars Phoenix Lander Site, but only very minor regional thaw was modelled as being possible there by Mellon et al. (2008) prior to the landing of Phoenix. Because the modelled amount of thaw fluid was deemed insufficient to be geomorphically effective, Mellon et al. (2008) and Levy et al. (2010) explained sorting to be a consequence of clast collapse into thermal contraction cracks in a dry environment characterized by sublimation, not thaw. However, sorted clastic mounds, nets, polygons and stripes are landforms widely associated on Earth with freeze-thaw cryoturbation (e.g., Kessler and Werner, 2003) and, as already described, neither the morphology nor the plan form organization of the martian sorted clastic landforms is accordant with underlying fracture patterns. Accordingly, periglacial freeze–thaw sorting offers a plausible explanation of the martian high-latitude morphological assemblage, including its spatial and clinometric contexts and the inter-relationships of its components.

Importantly, fluvial gullies are intimately tied to both sorted and non-sorted landforms in this region (e.g. Figure 9). Of the braided gullies identified, some predate, and others post-date ground patterned by cracks, polygons, circles and lobes (Gallagher and Balme, 2011; Gallagher et al., 2011). Once again, these landforms on Mars have a close analogue on Svalbard, where sorted lobes and patterned ground are spatially correlated with braided gullies and thermal contraction fractures (Johnsson et al., 2011). Levy et

al. (2009b) described gully-polygon interaction in the Dry Valleys of Antarctica that are also analogous to martian gully polygon associations, and they suggested a genetic link between martian gullies and periglacial/permafrost landform assemblages, including polygonally patterned ground (Levy et al., 2009a).

Gully erosion all the way back to the crater rim (e.g., Figure 9) suggests that these fluviatile systems (for a discussion of the characteristics of debris flow versus "fluvial" gullies on Mars see Reiss et al., 2011) are the product of incision by thaw fluids seeping from solifluction lobes, from frost melt or even from snow melt trapped in polygonal fracture networks (Levy et al., 2009b). However, other explanations such as rim flattening by creep and mass wasting, and extensive loss of crater-rim ground-ice reservoirs, cannot be excluded. Hence, from the co-association of these landforms, Gallagher et al. (2011), Gallagher and Balme (2011) and Johnsson, et al. (2011) inferred the widespread action of freeze-thaw in a fluvio-periglacial context.

In summary, lobate clastic and non-clastic features are close analogues of solifluction lobes on Earth. The association in time and space of apparent solifluction landforms and sorted stone stripes, circles and polygons with gullies suggests that there was at least enough liquid available for gully formation, although obtaining quantitative estimates of thaw rate or the volume of thaw liquid from morphology alone is difficult and only first-

order estimates can be made (Gallagher and Balme, 2011). Similarly, the association with polygonal fractures of probable thermal-contraction origin provide consilient evidence for ice in the regolith, and could be taken as evidence for a change in climate from wetter conditions when the solifluction lobes formed, to dryer when thermal contraction and sublimation dominated.

4.3. Equatorial Assemblage

This assemblage, described more fully in Balme and Gallagher (2009), is distinct from those previously discussed in that i) it pertains to a single locale at the head of the outflow channel 'Athabasca Valles', rather than a latitude range and ii) the proposed source of ice in the regolith was almost certainly fluvial floodwaters, rather than atmospheric precipitation or condensation. The evidence for thaw includes polygonally patterned surfaces hosting landforms analogous to retrogressive thaw slumps (RTS); merged basins (containing RTS and secondary polygonal patterned ground) that evolved through downwearing and backwearing; pingo-like cones and mounds within these basins; and apparent slope subsidence failures. The interpretation is that this assemblage of landforms reflects a relict thermokarst landscape that formed in icy sediments left behind after megaflooding, but it seems unlikely that such thaw-related processes are ongoing today.

This study area at the head of Athabasca Valles is near the equator (~10.2° N 157° E) and represents the source regions of a flood-carved outflow channel (Burr et al., 2002a; Burr et al., 2002b) that begins at a large fracture system called the Cerberus Fossae (Figure 10) and which is thought to be the source of the flood waters. The Athabasca Valles source region comprises two amphitheatre-shaped depressions which open to the southwest. These two depressions merge to form the main channel, which slopes away from the source region with a gradient of approximately 0.3° and a slightly concave long profile. The proximal five to ten kilometres of the channel slope back towards the source region and it is within this shallow basin that landforms interpreted to be indicative of thaw have been identified (Balme and Gallagher, 2009).

The basin floor south of the southern Cerberus Fossae fracture comprises a series of polygonally-patterned surfaces (Figure 11) and shallow basins. The surfaces are separated by distinctive scarps (Figure 11) indented by cirque-shaped indentations or niches, and broad, v-shaped ‘bays’. In Figure 11, scarp formation has apparently been by retrogressive erosion (cf. 'backwearing', Czudek and Demek, 1970) into the polygonised surface, accompanied by the contemporaneous (or immediately subsequent) release of debris and the stranding of large (meter-scale) clasts by the formation of dendritic channels at the base of the scarps. Remnant spurs appear to

demonstrate the minimum original extent of the upper surface prior to backwearing, which, given the size and shape of the smallest embayments, might have exploited the polygonised pattern of the upper surface (Balme and Gallagher, 2009).

The channels have a contributory form and, as shown in Figure 11, at least one example terminates at the margins of a shallow depression with a distinctive hummocky floor. Possible lobate flows with subtle leveed channels can be seen in this example. Hummocky material with similar morphology occurs at the terminations of other channel systems in this region. Balme and Gallagher (2009) suggest that these forms are analogous to terrestrial retrogressive thaw slumps (RTS): landforms that on Earth are diagnostic of degrading ice-rich permafrost (Harris, 1981).

Nearby, similar niche and spur scarp morphologies form the boundaries of linked basins (Figure 12). Importantly, polygonally patterned ground occurs on the sloping inner walls of these basins, beneath the niche-indented headwalls of the basin margins. If the scarps formed by retrogressive erosion, then this polygonization must be secondary in origin, and have formed after or as the backwearing occurred. Small gullies can be seen on the inner slopes of these basins, again suggesting fluvial erosion. The floors of these linked basins are hummocky and rough and contain small pitted-cone or pitted-mounds. These linked basins speak of significant downwearing and backwearing of enlarging

depressions, with some examples showing small outflow channels (e.g. at Z in Figure 12) which points to flow of fluid through 'tapping' (Hill and Solomon, 1999) channels as the basins expanded and merged. The evolutionary pattern of these linked basins and scarp systems implies liberation of a volatile from within the regolith. This volatile was probably water, given the regional flood-channel setting and the small gullies and fluvial-like channels seen here. If this is the case, these basins probably represent thermokarst depressions, and the mound and cone landforms are likely to be remnant pingos.

A nearby closed, shallow basin within the main Athabasca Channel (Figure 13) is surrounded by polygonal terrain and internally partitioned by low causeways of domed polygons or niche-indented headlands. Many of the niches, especially on the western margin of the basin, are fronted by scarp-parallel ridges that appear to have been formed by subsidence failures. The composite form of the basin suggests that it evolved from a series of smaller basins that became linked as they enlarged and merged. The basin contains groups of cone and mound landforms that are spatially associated with either the lowest points of the basin floor, or with channels feeding (or perhaps draining) the basin (e.g. Y, Figure 13). This association is consistent with a tapping model (Hill and Solomon, 1999) of basin evolution wherein fluid filled basins grow and merge with liquid transferring between them by small channels. The cone and mound landforms

display a range of morphologies, from simple mounds, through pitted cones, to cone groups situated within ramparts and moats. Some of the cone/mounds, especially in the southeast, appear degraded. Again, if the basin formed by thermokarst, these features are probably pingos, as has been suggested for other regions of Athabasca Valles (Burr et al., 2005; Page and Murray, 2006).

To summarise: 1) locally high, planar surfaces are modified by planar and domed polygons, 2) these surfaces are truncated by cirque-shaped scarps probably formed by failures along polygon edges, 3) the scarps are fronted by inclined slumps and flows modified again by domed polygons, 4) the slumps and flows are often incised by channels and gullies and often terminate at a break of slope marking the margin of 5) a hummocky, debris-floored basin, containing cone/mound landforms, 6) in gently sloping regions, these processes form linear scarps perpendicular to slopes; in flatter areas, autogenic basin formation and enlargement leads to complex topography.

Given both the consistent similarity between this assemblage and thermokarst landscapes on Earth, and the regional context of a flood-carved channel, the most likely explanation of these observations appears to be a linked mass wasting environment controlled by the thaw of ground ice in the locally uppermost surfaces. Subsidence has destroyed the original surface relief but new thermokarst relief has formed at a lower

elevation by both downwearing and backwearing (Czudek and Demek, 1970; French, 2007) The result is a landscape of self-similar elements reflecting multiple cycles of surface reworking by a single set of processes in which thaw plays a key role.

5. Discussion

5.1 Terrestrial analogues

In each of the three assemblages described, terrestrial analogues have been vital in understanding the landscape. While the use of terrestrial analogues is essential in any analysis of the martian landscape, it is also critical to recognize the limits of this approach, as vegetation (or lack thereof), mineralogy, rock type and landscape evolution, including the role of transitions between landscape convergence and divergence should all be taken into account but are often impossible to characterise with any certainty, let alone quantify. For example, the landscape of Svalbard provides very good morphological analogues of Mars, but its climatic conditions are significantly different from present martian conditions, and also different from what can reasonably be expected to have existed on Mars over the last few million years. Mars is, compared with terrestrial standards, exceptionally cold and dry, and from that viewpoint Svalbard could be regarded as a poor climatic analogue, despite the landform assemblages it

shares with Mars, such as those including patterned ground, sorted mass wasting slope deposits and gullies. Hyperarid cold deserts such as those found in places of the Canadian High Arctic, Greenland, or particularly in continental Antarctica may provide climatic conditions that are closer to those prevailing on Mars. Indeed the McMurdo Dry Valleys of Antarctica have a long history as analogues for different aspects of Mars studies (e.g., Chapman, 2007; Doran et al., 2010; Marchant and Head, 2007) and an interpretation of some martian landforms based on the hyperarid polar desert analogue yields very plausible results, as in the case of Antarctic sand-wedge polygons. However, not all features (e.g., slope stripes and solifluction lobes) observed on Mars have analogues in the coldest, driest regions of terrestrial cold deserts (e.g., the 'stable upland zone' of the Antarctic Dry Valleys described by Marchant and Head, 2007) that are most Mars-like in climate. So, there is probably no single analogue landscape on Earth that can serve to explain all the observed characteristics of martian landscape. However, terrestrial landscapes still provide vital analogues, as they demonstrate how landscapes are shaped by different processes and involve variable degrees of morphological inheritance from earlier process environments. Hence, it is important to note that there are regions on Earth that are good process analogues, and others that are good climate analogues (and some areas that are both) as well as recognizing that while morphology can sometimes be process-specific, processes are not generally climatically specific, so linking morphology directly to climate in an absolute sense is extremely challenging.

5.2 Evidence for thaw

In the mid-latitudes on Mars, the presence of a suite of landforms associated with ice strengthens the arguments that both gullies and pro- and supraglacial valleys were formed by melt of ice to form liquid water. Without the presence of landforms indicative of ice, it would be difficult to imagine how liquid water could be generated, unless by seepage or outburst from underground (and this has been shown to be unlikely, at least for gullies; Balme et al., 2006; Dickson and Head, 2009; Reiss et al., 2009). By way of confirmation that martian gullies were not formed by dry processes, Conway et al. (2011a) used morphometric terrain analysis techniques to show that martian gullies are more similar to 'wet' terrestrial debris flow chutes than they are to dry, colluvial fans. This approach provides a way around the problem of equifinality brought up by Bart (2007), who suggested gullies on the Moon (presumably formed by water-free processes) are morphologically similar to gullies on Mars. However, such techniques are not universally applicable, for they require very high spatial resolution topographic data that are available only for a few areas of Mars, and are restricted to certain classes of hillslope landform. Nevertheless, as more high fidelity topographic data are returned from Mars and other planets, such quantitative techniques could provide an additional way to infer process from form.

Similarly, the solifluction lobes and sorted patterned ground seen at high latitudes are themselves strong evidence for the presence of freeze-thaw cycles, but the key observation supporting this interpretation is their spatial and temporal associations with gullies (indicating liquid water flow) and a variety of polygonally patterned ground (indicating the presence of water-ice). The simplest interpretation of this landscape is that there was water-ice within and/or covering the regolith and that, at some point in the recent past, thaw of ice or snow led to sufficiently intense incision (perhaps generated only by rare short-lived events) to form the gullies, the sorted landforms having been formed by freeze-thaw processes within the regolith. This hypothesis is consilient with all the local geomorphology. Conversely, hypotheses for formation of sorted ground in this region based solely on dry processes seem unlikely (e.g., Orloff et al., 2012; Orloff et al., 2011), as they explain neither the gullies nor the lobate forms. It is likely that most of the high latitude patterned ground seen on Mars did not form by thaw-related processes (Levy et al., 2009a; Mellon et al., 2008), particularly across the extensive, flat plains regions in the northern martian lowlands, but this does not mean that thaw, as described here, was not a gemomorphic agent in numerous high latitude local examples.

The low latitude assemblage described at the head of Athabasca Valles appears to be best explained by thaw of ice-rich flood deposits. This landscape probably formed out

of equilibrium with the climate, unlike the other assemblages where both deposition and removal of ice has likely been climate controlled, for its characteristic morphologies and their spatial organisation are determined by the spatial pattern and morphology of surface floodwater storage sinks and deposits. Certainly, there is no evidence for ice or thaw related landforms immediately outside of the putatively flood-related terrain. In some ways, the presence of thaw here is not unexpected. The sudden deposition of massive amounts of ice, water and debris onto the surface in a region near Mars' equator would have meant that conditions for thaw would be optimum in terms of temperature. However, it should be noted that these same polygonally patterned ground have been interpreted by some researchers (e.g., Jaeger et al., 2010; Keszthelyi et al., 2000; Keszthelyi et al., 2004; Plescia, 1990; Ryan and Christensen, 2012) to be primary extrusive volcanic deposits, rather than the expression of secondary modification of ice-rich flood sediments (e.g., Balme and Gallagher, 2009; Burr et al., 2005; Page, 2007), although no volcanic interpretation has yet been advanced that explains all the landforms and their spatial association in this specific location in the same way that the thermokarst hypothesis does. Both interpretations might be correct to some extent, for the periglacial assemblage could have developed within or on top of primary volcanic material after the water ice and sediments were brought in following flooding.

The geologically recent thaw-modified landscapes described here are distributed around the globe, and at low to high latitudes. Those landscapes including features such as stone circles, stripes and solifluction-like lobes are perhaps indicative not only of surface melt, but also of ground ice thawing cycles. Similarly, observations and surveys of populations of gullies provide evidence for surface thaw (at least for those gullies found on polygonised substrates; Levy et al., 2009b) from mid to high latitudes in both hemispheres (e.g, Balme et al., 2006; Kneissl et al., 2009; Malin and Edgett, 2000). Hence geologically recent thaw appears to be fairly common on Mars. Nevertheless, compared with other morphological indicators of ice (but not thaw) such as polygonally patterned grounds interpreted to be thermal contraction fractures (e.g., Levy et al., 2009a; Mangold, 2005; Mellon, 1997) the distribution of thaw related landforms is spatially very restricted. Hence, thaw is not likely to have been a globally dominant process in the recent past, but as the examples shown above demonstrate, local examples of thaw can be found globally.

5.3 Hypotheses to explain thaw

One broad interpretation of the martian geomorphology described in this paper is that both fluid flow and freeze-thaw cycles have, to some extent, shaped the surface throughout the mid- and high-latitudes in the recent past, and that these processes have

even occurred in specific process environments near the equator. However, given the inhospitality of the current martian environment to liquid water, this leads to an apparent paradox – the landscape appears to be shaped by liquid water, but thaw of ice to produce liquid water under today's cold and dry climate is not predicted in general (Ingersoll, 1970). This is because near-surface ground ice on Mars sublimes in the low humidity conditions, except nearer the poles where the temperatures are colder and hence the saturation point and sublimation rate lower. Hence to melt, ice must either be warmed sufficiently quickly for sublimation cooling to be offset, or diffusion of water vapour from the ice must be minimized such that sublimation is restricted. These criteria can be met only under specific conditions such as coating by dust, overlying and removal of CO_2 ice, or the presence of salts, (see, for example, the summary section of Hecht, 2002). It should also be noted, though, that surface liquid water can remain in disequilibrium long enough to do significant geomorphic work and flow significant distances if it can be produced quickly enough (e.g., Heldmann et al., 2005; Conway et al., 2011b) even under present day conditions.

A first possible solution to this paradox is that brines with low freezing points (cryobrines) are the active geomorphological agents rather than pure water. Some brines can remain liquid at temperatures tens of degrees colder than the freezing point of pure water (e.g., Knauth and Burt, 2002; Möhlmann and Thomsen, 2011). The detection of

perchlorate at the Phoenix landing site (Hecht et al., 2009) has provided observational evidence for salts on Mars that have a low eutectic temperature and might allow for the possibility of liquid brines today (e.g., Marion et al., 2009). Magnesium, calcium and sodium are possible anion pairs (Hecht et al., 2009) and their perchlorates all have eutectic temperatures below 240 K (Marion et al., 2009; Pestova et al., 2005). Interestingly, the eutectic temperature of magnesium perchlorate is within the range of spring/summer diurnal variations modelled and measured for the Phoenix Landing Site (Zent et al., 2010). The most recently discovered 'wet' landforms – recurring slope lineae (McEwen et al., 2011) – are forming on Mars at the present time, most likely associated with active, but spatially uncommon, flows of cryobrines at low temperatures and in a thin, dry atmosphere

A second solution to the apparent paradox is the possibility that those landforms attributed to thaw processes (e.g. gullies, sorted stripes and circles, clastic lobes) are a climatically controlled assemblage, reflecting significantly warmer conditions than those prevailing now. This hypothesis maintains that it was melt of water-ice to form liquid water at ~273 K that shaped the landscape, rather than the action of cryobrines acting under a climate similar to the present-day. For example, Kreslavsky et al. (2008) calculate that an active layer (i.e. near-surface temperatures consistently above 273K) can develop on Mars due to changes in the climate driven by ~ 120 ka cycles in

obliquity. Such conditions might allow thaw in suitable microclimates, even if the global climate was unsuited to regional melt of water ice. Similar mechanisms have been proposed to explain the formation of gullies on Mars (e.g., Christensen, 2003; Costard et al., 2002; Dickson and Head, 2009; Levy et al., 2009b; Williams et al., 2009). In contrast, though, the present activity of recurring slope lineae seems to show liquid-based activity under present day conditions, although it should be noted that at the time of writing, recurring slope lineae have been found in very few locations compared with gullies or other putative thaw-related landforms. Also, the presence of a relict thermokarst assemblage near the martian equator demonstrates that local-to-regional inheritance of form and materials can play a crucial role in modulating morphogenetic responses to prevailing climate.

The small size and lack of degradation of many of the landforms and landscapes described here mean that it is difficult to determine their age based on the size frequency statistics of superposed impact craters or erosion rate estimates, so it is extremely challenging to determine whether any given landform formed under current or recent past climatic conditions, unless that landform can be observed to change. In addition, the two hypotheses proposed are not exclusive, and perhaps both were valid at different locations and times.

5.4 Can these hypotheses be tested?

The first hypothesis is difficult to test without in-situ studies to confirm the chemical composition of, for example, deposits or surfaces associated with thaw-related landforms. Hyperspectral remote sensing studies (e.g., Murchie and the CRISM Science Team, 2007) might also be used by measuring the reflectance spectra of minerals in the regions where, for example, recurring slope lineae are forming. Current instruments probably lack the spatial resolution for this task, however: initial studies of the recurring slope lineae McEwen et al. (2011) find that hydrated minerals are associated with bedrock at several sites where recurring slope lineae have formed (including phyllosilicates in Asimov Crater and chlorite, kaolinite, and hydrated silica in the central structure of Horowitz Crater) but they do not find a correlation between recurring slope lineae regions and particular minerals. Laboratory studies aimed at testing whether phase changes in hydrated minerals can perform the same geomorphological work that freeze-thaw of ice does could also be used to, at the least, demonstrate that the hypothesis is plausible.

The second hypothesis has been investigated in some detail, and more work is underway. For example, Kreslavsky et al. (2008) used a model of Mars' past obliquity and eccentricity (from Laskar et al., 2004) to calculate spatial variations in peak

insolation over the past few million years on Mars. They found that seasonal thaw waves (>273 K) penetrating to tens of centimetres depths could have occurred in several periods during the last 20 Ma. Kreslavsky et al. (2008) also found that local slope, albedo, and regolith properties play a significant role in determining the depth of such an active layer. They note also that active layer formation is rather rare, and that it is only on steep slopes at high latitudes, during high obliquity periods, that an active layer might develop (cf. section 4.3 above). Whether liquid water could form from segregation ice or pore ice and then remain stable against boiling and evaporation within the regolith long enough to do significant geomorphological work is unknown, and would depend mainly on the properties of the regolith and the rate at which water-vapour would diffuse from it (Hudson et al., 2007). Furthermore, Möhlmann (2010) suggests that the 'solid-state greenhouse effect' allows insolation energy to be absorbed within snow or ice packs, allowing internal ice or snow to heat up and perhaps even melt, while the upper surface remains at sub-freezing temperatures. He calculates that melt of snow or ice is possible under present-day condition on Mars, at least for some regions and deposits. This mechanism might be important for generating melt within the source regions of gullies, although it is less relevant to the melting of ground-ice and the formation of patterned ground.

5.5 Implications of thaw

The formation of liquid water on Mars seems possible, but requires special circumstance – either the presence of optically thin snow and ice deposits to create a solid-state greenhouse, climate change in the recent past, or the presence of salts that can depress the freezing point of the water. If it can be determined which (if any) of these process-suites were responsible for creating the thaw-related landscapes described here, this raises the question as to whether geomorphological observations can be used to provide information about past environment on Mars. Of course, inferring environment from landform is difficult, even on Earth. Current landscapes can still display an imprint of former climatic conditions (e.g., André, 2003; French, 2007; Twidale, 1999) so disentangling signals from remote sensing alone is a challenge. Also, as has been demonstrated for the Earth (e.g., Matsuoka, 2011; Murton and Kolstrup, 2003), it is unlikely that any single landform can be used as a quantitative indicator of past and/or present climatic conditions. Nevertheless, as the martian landscape is a simpler system than on Earth, with no plate tectonics, no vegetation, less water, and lower erosion rates, it is possible that the link between climate and landforms on Mars could be more direct.

In summary, although the morphological signatures of thaw are now becoming better-recognized, a lot of work remains to be done if these observations are to be placed into a

consistent framework explaining how Mars' surface and climate have evolved in the past few million years.

6. Ongoing and future directions for research

Identification of many of the landforms described here has only been possible since HiRISE images with sub-meter resolution became available in 2006. Hence, this branch of martian geomorphology is advancing particularly quickly. For example, while decametre-scale patterned ground at high-latitude on Mars has been well documented for over a decade (e.g., Levy et al., 2009a; Levy et al., 2010; Mangold, 2005; Mellon, 1997; Seibert and Kargel, 2001) and all of these authors considered thaw as a geomorphic process in polygon formation, it has largely been rejected on the weight of the evidence. Yet in the past two years, solifluction-like landforms within these regions have been described in four papers (Gallagher et al., 2011; Gallagher and Balme, 2011; Hauber et al., 2011a; Johnsson et al., 2011). HiRISE images cover less than a few percent of the surface, and more images are being acquired daily, so most of Mars remains unexplored at this scale and the study of possible solifluction lobes and sorted patterned ground on Mars is still, therefore, rather in its infancy. To help constrain how such landscapes evolved, and under what climate conditions, a primary data set describing both the global distribution of such landforms, and their regional-scale

geological context is needed. Such work might also explain the observations that, in the high- and mid-latitudes, many of the landforms indicative of thaw, such as gullies, sorted stripes and solifluction lobe-like features, occur on steep slopes. This is consistent with models of martian active layer formation (Kreslavsky et al., 2008) on Mars, and liquid water stability (Hecht, 2002). Interestingly, the low latitude assemblage described is in a flat region, but has a different suite of landforms. Hence, it would be informative to compare the different morphologies and assemblages with high resolution terrain models as well as to regional and local climate models.

While some landforms such as recurring slope lineae are forming today, perhaps most landforms indicative of freeze/thaw did not form on present-day Mars, but during periods with different climates. To test this hypothesis, a much better understanding of the martian climate in the last ~20 Ma as a function of obliquity and other orbital parameters is required. Such information would help to constrain precipitation patterns, the frequency of freeze/thaw cycles and the associated amount of liquid water available (if any). Advances in assessment of past environmental conditions will come from climate modelling at different scales (including meso-scale models and the analysis of local relief-dependent microclimates).

As described in section 5.3, some hydrated minerals have the capacity to capture, store, and release large amounts of water from their chemical structures at temperatures well below 273 K. Hence these processes could be important on cold Mars, playing the same geomorphic role the water-ice transition does in periglacial regions on Earth. However, not enough is known about the behaviour of these materials under martian conditions to verify whether they can play such a role in shaping the surface. Laboratory investigation of their behaviour as a function of past and present martian temperature, regolith-cover, and interaction with ground ice is needed. A particularly important early study could be to simulate the conditions at which the recurring slope lineae (McEwen et al., 2011) formed, in order to investigate whether salt/regolith/ice mixtures could generate liquids as seasonal conditions change as suggested (McEwen et al., 2011).

Although periglacial landforms have been observed on Mars and are thought to be 'young' due to the lack of superposing impact craters, the rates at which periglacial processes operate on Mars, inferred from these morphologies, are unknown. It might be envisaged that they operate orders of magnitudes slower than on Earth, for liquid water is probably available only episodically, in small amounts, and in spatially and/or temporally restricted circumstances. Coupled with Mars' low erosion rates, this would perhaps offer an explanation why we observe apparently young periglacial landforms on Mars: the same process might shape a landform very quickly on Earth (e.g., on post-

glacial surfaces in the Holocene, within thousands of years) if substantial amounts of liquid water are available, but could require hundreds of thousands or even millions of years to form an analogous landform under current martian conditions. Dating martian periglacial surfaces and landforms by the statistical analysis of the numbers of very small impact craters superposing them would be a challenging (especially given the ongoing controversy surrounding the use of small crater counts as a dating tool; e.g., Hartmann, 2007; McEwen and Bierhaus, 2006), but productive, future area for research

More field studies are needed to help understand terrestrial landscapes as periglacial process-analogues for Mars, and to understand how climate controls or modifies these processes. This is, of course, a broad question, but the contrasting hyperarid polar desert climate of the Dry Valleys in Antarctica and the periglacial cold and relatively moist (although still close to polar desert conditions) climate of Svalbard provide a good starting point for Mars research. Both locations provide suites of periglacial landforms that are good process and morphological analogues for Mars, yet the details of the assemblages are different. Interestingly, certain martian regions (especially at high latitude) contain landforms directly analogous to examples from both Svalbard and Antarctica. Hence, it would be instructive to learn more about when, how fast, and under what climatic conditions the terrestrial landforms were created, for this could provide important constraints on the environments under which the martian landforms

were formed, and how the landscape evolved as – presumably – climate changes occurred.

Finally, an underlying methodological aspiration vital for this type of research is to find a way to determine how much meltwater is involved in martian landscape development. Such an approach could help discriminate between wet versus dry morphogenesis, and even between surface melt (of ice or snow) and subsurface melt (i.e. active layer formation). Connecting the extent of thaw needed to form the various landforms to the overall landscape thaw generation potential could be a very valuable way of recasting and testing the climate implications of various landscape analyses. Attempts to follow such a methodology using both qualitative (e.g., Hauber et al., 2011a) and quantitative terrain analyses (e.g., Conway et al., 2011a) are already making progress.

6. References

Aharonson O and Schorghofer N. (2007) Subsurface ice on Mars with rough topography. *J. Geophy. Res.* 111: doi:10.1029/2005JE002636

Albee AL, Arvidson RE, Palluconi F, et al. (2001) Overview of the Mars Global Surveyor mission. *J. Geophys. Res.* 106: 23,291-223,316.

André, M-F. (2003) Do periglacial landscapes evolve under periglacial conditions? *Geomorphology* 52: 149-164.

Ansan V and Mangold N. (2006) New observations of Warrego Valles, Mars: evidence for precipitation and surface runof. *Plan. Space Sci.* 54: 219-242.

Baker VR. (2001) Water and the martian landscape. *Nature* 412: 228-236.

Baker VR, Strom RG, Gulick VC, et al. (1991) Ancient oceans, ice sheets, and the hydrological cycle on Mars. *Nature* 352: 589-594.

Ballantyne CK and Harris C. (1994) *The periglaciation of Great Britain,* Cambridge: Cambridge University Press.

Balme MR and Gallagher C. (2009) An equatorial periglacial landscape on Mars. *Earth Planet. Sci. Let.* 285: 1-15.

Balme MR, Gallagher C, Page DP, et al. (2009) Sorted stone circles in Elysium Planitia, Mars: implications for recent martian climate. *Icarus* 200: 30-38.

Balme MR, Mangold N, Baratoux D, et al. (2006) Orientation and distribution of recent gullies in the southern hemisphere of Mars: observations from HRSC/MEX and MOC/MGS data. *J. Geophys. Res.*: E05001, doi: 05010.01029/02005JE002607.

Bargery AS, Balme MR, Warner N, et al. (2011) A background to Mars exploration and research. In: Balme MR, Bargery AS, Gallagher CJ, et al. (eds) *Martian Geomorphology*. London: Geological Society., 5-20.

Bart G. (2007) Comparison of small lunar landslides and martian gullies. *Icarus* 187: 417-421.

Berthling I. (2011) Beyond confusion: Rock glaciers as cryo-conditioned landforms. *Geomorphology* 131: 98-106.

Boynton WV, Feldman WC, Squyres SW, et al. (2002) Distribution of hydrogen in the near surface of Mars: Evidence for subsurface ice deposits. *Science* 297: 81-85.

Burr DM, Grier JA, McEwen AS, et al. (2002a) Repeated Aqueous Flooding from the Cerberus Fossae: Evidence for Very Recently Extant, Deep Groundwater on Mars. *Icarus* 159: 53-73.

Burr DM, McEwen AS and Sakimoto SEH. (2002b) Recent aqueous floods from the Cerberus Fossae, Mars. *Geophysical Research Letters* 29: doi:10.1029/2001GL013345.

Burr DM, Soare RJ, Wan Bun Tseung, J-M, et al. (2005) Young (late Amazonian), near-surface, ground ice features near the equator, Athabasca Valles, Mars. *Icarus* 178: 56-73.

Burr DM, Tanaka KL and Yoshikawa K. (2009) Pingos on Earth and Mars. *Plan. Space Sci.* 57: 541-555.

Byrne S, Dundas CM, Kennedy MR, et al. (2009) Distribution of mid-latitude ground ice on Mars from New impact craters. *Science* 325: 1674-1676.

Carr MH. (1987) Water on Mars. *Nature* 326: 30-35.

Carr MH. (2000) Martian oceans, valleys and climate. *Astron. Geophys.* 41: 3.20-23.26, doi: 10.1046/j.1468-4004.2000.00320.x.

Carr MH and Schaber GG. (1977) Martian permafrost features. *J. Geophy. Res.* 82: 4039-4054.

Chapman MG. (2007) The geology of Mars: evidence from Earth-based analogs. Cambridge: Cambridge University Press.

Chicarro A, Martin P and Traunter R. (2004) Chicarro, A., Martin, P., Traunter, R. In: Wilson A (ed) *Mars Express: a European Mission to the Red Planet, SP-1240.* Noordwijk: European Space Agency Publication Division.

Christensen P. (2003) Formation of recent martian gullies through melting of extensive water-rich snow deposits. *Nature* 422: 45-48.

Conway SJ, Balme MR, Murray JB, et al. (2011a) The determination of martian gully formation processes by slope-area analysis. In: Balme MR, Bargery AS, Gallagher C, et al. (eds) *Martian Geomorphology.* London: Geological Society of London, Special Publications, 171-201.

Conway SJ, Lamb MP, Balme MR, et al. (2011b) Enhanced runout and erosion by overland flow at low pressure and sub-freezing conditions: Experiments and application to Mars. *Icarus* 211: 443-457.

Costard F, Forget F, Mangold N, et al. (2002) Formation of recent martian debris flows by melting of near-surface ground ice at high obliquity. *Science* 295: 110-113.

Costard FM and Kargel JS. (1995) Outwash plains and thermokarst on Mars. *Icarus* 114: 93-112.

Craddock RA and Howard AD. (2002) The case for rainfall on a warm, wet early Mars. *J. Geophy. Res.* 107: doi:10.1029/2001JE001505.

Czudek T and Demek J. (1970) Thermokarst in Siberia and its influence on the development of lowland relief. *Quat. Res.* 1: 103-120.

Dickson JL, Fassett CI and Head JW. (2009) Amazonian-aged fluvial valley systems in a climatic microenvironment on Mars: Melting of ice deposits on the interior of Lyot Crater. *Geophys. Res. Let.* 36: doi:10.1029/2009GL037472.

Dickson JL and Head JW. (2009) The formation and evolution of youthful gullies on Mars: Gullies as the late-stage phase of Mars' most recent ice age. *Icarus* 204: 63-86.

Dickson JL, Head JW and Kreslavsky MA. (2007) Martian gullies in the southern mid-latitudes of Mars: Evidence for climate-controlled formation of young fluvial features based upon local and global topography. *Icarus* 188: 315-323.

Diniega S, Byrne S, Bridges N, et al. (2010) Seasonality of present-day Martian dune-gully activity. *Geology* 38: 1047-1050.

Doran PT, Lyons WB and McKnight DM. (2010) Life in Antarctic Deserts and other Cold Dry Environments. Cambridge: Cambridge University Press.

Dundas CM, Keszthelyi LP, Bray VJ, et al. (2010a) Role of material properties in the cratering record of young platy-ridged lava on Mars. *Geophys. Res. Let.* 37: doi:10.1029/2010GL042869.

Dundas CM and McEwen AS. (2010) An assessment of evidence for pingos on Mars using HiRISE. *Icarus* 205: 244-258.

Dundas CM, McEwen AS, Diniega S, et al. (2010b) New and recent gully activity on Mars as seen by HiRISE. *Geophys. Res. Let.* 37: doi: 10.1029/2009GL041351.

El Maarry MR, Markiewicz WJ, Mellon MT, et al. (2010) Crater floor polygons: Desiccation patterns of ancient lakes on Mars? *J. Geophys. Res.* 115: doi: 10.1029/2010JE003609.

Fairen AG. (2010) A cold and wet Mars. *Icarus* 208: 165-175.

Fassett CI, Dickson JL, Head JW, et al. (2010) Supraglacial and proglacial valleys on Amazonian Mars. Icarus, 208, 86-100. *Icarus* 208: 86-100.

Fastook JL, Head JW, Marchant DR, et al. (2012) Early Mars climate near the Noachian–Hesperian boundary: Independent evidence for cold conditions from basal melting of the south polar ice sheet (Dorsa Argentea formation) and implications for valley network formation. *Icarus* 219: 25-40.

Feldman WC, Mellon MT, Gasnault O, et al. (2007) Vertical distribution of hydrogen at high northern latitudes on Mars: The Mars Odyssey Neutron Spectrometer. *Geophys. Res. Let.* 34: doi:10.1029/2006GL028936.

Feldman WC, Prettyman TH, Maurice S, et al. (2004) The global distribution of near-surface hydrogen on Mars. *J. Geophys. Res.* 109: doi:10.1029/2003JE002160.

French HM. (2007) *The Periglacial Environment, 3rd edn.,* Chichester: John Wiley and Sons.

Gallagher C and Balme MR. (2011) Landforms indicative of ground-ice thaw in the northern high latitudes of Mars. In: Balme MR, Bargery AS, Gallagher CJ, et al. (eds) *Martian Gemorphology.* London: Geological Society of London Special Publications, 87-110.

Gallagher C, Balme MR, Conway SJ, et al. (2011) Sorted clastic stripes, lobes and associated gullies in high-latitude craters on Mars: Landforms indicative of very recent, polycyclic ground-ice thaw and liquid flows. *Icarus* 211: 458-471.

Golombek MP and Bridges NT. (2000) Erosion rates on Mars and implications for climate change: Constraints from the Pathfinder landing site. *J. Geophys. Res.* 105: 1841-1853.

Harris C. (1981) *Periglacial Mass-wasting: A review of Research,* Norwich: GeoAbstracts.

Hartmann WK. (2007) Martian cratering 9: Toward resolution of the controversy about small craters *Icarus* 189: 274-278.

Hartmann WK and Neukum G. (2001) Cratering Chronology and the Evolution of Mars. *Space Sci. Rev.* 96: 165-194.

Hauber E, Reiss D, Ulrich M, et al. (2011a) Landscape evolution in Martian mid-latitude regions: insights from analogous periglacial landforms in Svalbard. In: Balme MR, Bargery AS, Gallagher CJ, et al. (eds) *Martian Geomorphology.* London: Geological Society of London, Special Publications, 111-131.

Hauber E, Reiss D, Ulrich M, et al. (2011b) Periglacial landscapes on Svalbard: Terrestrial analogs for cold-climate landforms on Mars. In: Garry WB and

Bleacher JE (eds) *Analogs for Planetary Exploration: Geological Society of America Special Paper 483*. doi:10.1130/2011.2483(1112) in press.

Hauber E, van Gasselt S, Chapman MG, et al. (2008) Geomorphic evidence for former lobate debris aprons at low latitudes on Mars: Indicators of the Martian paleoclimate. *J. Geophy. Res.* 113: doi:10.1029/2007JE002897.

Head JW, Marchant DR, Dickson JL, et al. (2010) Northern mid-latitude glaciation in the Amazonian period of Mars: Criteria for the recognition of debris-covered glacier and valley glacier landsystem deposits. *Earth Planet. Sci. Let.* 294: 306-320.

Head JW, Marchant DR and Kreslavsky MA. (2008) Formation of gullies on Mars: Link to recent climate history and insolation microenvironments implicate surface water flow origin *P. Natl. Acad. Sci. USA* 105: 13,258-213,263.

Head JW, Mustard JF, Kreslavsky MA, et al. (2003) Recent ice ages on Mars. *Nature* 426: 797-802.

Hecht MH. (2002) Metastability of water on Mars. *Icarus* 156: 373-386.

Hecht MH, Kounaves SP, Quinn RC, et al. (2009) Detection of Perchlorate and the Soluble Chemistry of Martian Soil at the Phoenix Lander Site. *Science* 325: 64-67.

Heldmann JL, Johansson H, Carlsson E, et al. (2005) Northern hemisphere gullies on Mars: Analysis of spacecraft data and implications for formation mechanism. XXXVI.

Hess SL, Henry RM, Leovy CB, et al. (1977) Meteorological measurements from the surface of Mars: Viking 1 and 2. *J. Geophys. Res.* 82: 4559-4574.

Hill PR and Solomon S. (1999) Geomorphologic and Sedimentary Evolution of a Transgressive Thermokarst Coast, Mackenzie Delta Region, Canadian Beaufort Sea. *J. Coastal Res.* 15: 1011-1029.

Holt JW, Safaeinili A, Plaut JJ, et al. (2008) Radar Sounding Evidence for Buried Glaciers in the Southern Mid-Latitudes of Mars. *Science* 322: 1235-1238.

Howard AD and Moore EJ. (2011) Late Hesperian to early Amazonian midlatitude Martian valleys: Evidence from Newton and Gorgonum basins. *J. Geophy. Res.* 116: doi:10.1029/2010JE003782.

Hubbard B, Milliken RE, Kargel JS, et al. (2011) Geomorphological characterisation and interpretation of a mid-latitude glacier-like form: Hellas Planitia, Mars. *Icarus* 211: 330-346.

Hudson TL, Aharonson O, Schorghofer N, et al. (2007) Water vapor diffusion in Mars subsurface environments. *J. Geophys. Res.* 112: doi:10.1029/2006JE002815.

Ingersoll AP. (1970) Mars: Occurrence of liquid water. *Science* 168: 972-973.

Irwin RP, Craddock RA and Howard AD. (2005) Interior channels in Martian valley networks: Discharge and runoff production. *Geology* 33: 489-492.

Jaeger WL, Keszthelyi LP, Skinner JA, et al. (2010) Emplacement of the youngest flood lava on Mars: A short, turbulent story. *Icarus* 205: 230–243.

Jakosky BM. (2007) *An astrobiology strategy for the exploration of Mars,* Washington DC: National Academies Press.

Jakosky BM and Farmer CB. (1982) The Seasonal and Global Behavior of Water Vapor in the Mars Atmosphere: Complete Global Results of the Viking Atmospheric Water Detector Experiment. *J. Geophy. Res.* 87: 2999-3019.

Johnsson A, Reiss D, Hauber E, et al. (2011) Periglacial mass-wasting landforms on Mars suggestive of transient liquid water in the recent past: Insights from solifluction lobes on Svalbard. *Icarus*: in press.

Johnsson A, Reiss D, Hauber E, et al. (2012) Periglacial mass-wasting landforms on Mars suggestive of transient liquid water in the recent past: Insights from solifluction lobes on Svalbard. *Icarus* 218: 489-505.

Kessler MA and Werner BT. (2003) Self-Organization of Sorted Patterned Ground. *Science* 299: 380-383.

Keszthelyi L, McEwen AS and Thordarson T. (2000) Terrestrial analogs and thermal models for Martian flood lavas. *J. Geophys. Res.* 105: 15027-15050.

Keszthelyi L, Thordarson T, McEwen AS, et al. (2004) Icelandic analogs to Martian flood lavas. *Geochem. Geophys. Geosys.* 5: doi:10.1029/2004GC000758.

Kieffer HH, Martin TZ, Peterfreund AR, et al. (1977) Thermal and albedo mapping of Mars during the Viking primary mission. *J. Geophys. Res.* 82: 4249-4291.

Knauth LP and Burt D. (2002) Eutectic brines on Mars: origin and possible relation to young seepage features. *Icarus* 158: 267-271.

Kneissl T, Reiss D, Van Gasselt S, et al. (2009) Distribution and orientation of northern-hemisphere gullies on Mars from the evaluation of HRSC and MOC-NA data. *Plan. Space Sci.* 294: 357-367.

Kreslavsky MA. (2008) Slope steepness of channels and aprons: implications for origin of martian gullies. *Workshop on martian gullies: Theories and Tests.* LPI, Houston: #8034.

Kreslavsky MA, Head JW and Marchant DR. (2008) Periods of active permafrost layer formation during the geological history of Mars: Implications for circum-polar and mid-latitude surface processes. *Plan. Space Sci.* 56: 289-302.

Lanagan PD, McEwen AS, Keszthelyi L, et al. (2001) Rootless cones on Mars indicating the presence of shallow equatorial ground ice in recent times. *Geophysical Research Letters* 28: 2365-2367.

Laskar J, Correia ACM, Gastineau M, et al. (2004) Long term evolution and chaotic diffusion of the insolation quantities of Mars. *Icarus* 170: 343-364.

Lefort A, Russell PS, Thomas N, et al. (2009) Observations of periglacial landforms in Utopia Planitia with the High Resolution Imaging Science Experiment (HiRISE). *J. Geophy. Res.* 114: doi:10.1029/2008JE003264.

Levy JS. (2012) Hydrological characteristics of recurrent slope lineae on Mars: Evidence for liquid flow through regolith and comparisons with Antarctic terrestrial analogs. *Icarus* 219: 1-4.

Levy JS, Head JW and Marchant DR. (2009a) Thermal contraction crack polygons on Mars: Classification, distribution, and climate implications from HiRISE observations. *J. Geophy. Res.* 114: doi: 10.1029/2008JE003273.

Levy JS, Head JW, Marchant DR, et al. (2009b) Geologically recent gully–polygon relationships on Mars: Insights from the Antarctic Dry Valleys on the roles of permafrost, microclimates, and water sources for surface flow. *Icarus* 209: 113-126.

Levy JS, Head JW, Marchant DR, et al. (2008) Identification of sublimation-type thermal contraction crack polygons at the proposed NASA Phoenix landing site: Implications for substrate properties and climate-driven morphological evolution. *Geophys. Res. Let.* 35: doi:10.1029/2007GL032813.

Levy JS, Marchant DR and Head JW. (2010) Thermal contraction crack polygons on Mars: A synthesis from HiRISE, Phoenix, and terrestrial analog studies. *Icarus* 206: 229-252.

Li H, Robinson MS and Jurdy DM. (2005) Origin of martian northern hemisphere mid-latitude lobate debris aprons. *Icarus* 176: 382-394.

Lucchitta BK. (1981) Mars and Earth: Comparison of Cold Climate Features. *Icarus* 45: 264-303.

Lucchitta BK. (1984) Ice and debris in the fretted terrain, Mars. J. Geophy. Res. 89(B1), B409-B419. . *J. Geophy. Res.* 89: B409-B419.

Malin MC and Edgett KS. (2000) Evidence for recent groundwater seepage and surface runoff on Mars. *Science* 288: 2330-2335.

Malin MC, Edgett KS, Posiolova LV, et al. (2006) Present day impact cratering rate and contemporary gully activity on Mars. *Science* 314: 1573-1577.

Mangold N. (2005) High latitude patterned ground on Mars: Classification, distribution and climatic control. *Icarus* 174: 336-359.

Mangold N, Mangeney A, Migeon V, et al. (2010) Sinuous gullies on Mars: Frequency, distribution, and implications for flow properties. *J. Geophy. Res.* 115: doi: 10.1029/2009JE003540.

Mangold N, Quantin C, Ansan V, et al. (2004) Evidence for Precipitation on Mars from Dendritic Valleys in the Valles Marineris Area *Science* 305: 78-81.

Marchant DR and Head JW. (2007) Antarctic dry valleys: Microclimate zonation, variable geomorphic processes, and implication for assessing climate change on Mars. *Icarus* 192: 187-222.

Marion GM, Catling DC, Claire M, et al. (2009) Modeling aqueous perchlorate chemistries with application to Mars. *Lunar Plan. Sci. XL [CDROM]*: Abstr. 1959.

Marquez A, Fernandez C, Anguita F, et al. (2004) New evidence for a volcanically, tectonically, and climatically active Mars. *Icarus* 172: 573-581.

Matsuoka N. (2011) Climate and material controls on periglacial soil processes: Toward improving periglacial climate indicators. *Quat. Res.* 75: 356-365.

McEwen AS and Bierhaus EB. (2006) The importance of secondary cratering to age constraints on planetary surfaces. *Annu. Rev. Earth Planet. Sci.* 34: 535-567.

McEwen AS, Ojha L, Dundas CM, et al. (2011) Seasonal flows on warm Martian slopes. *Science* 333: 740-743.

Mellon MT. (1997) Small-scale polygonal features on Mars: Seasonal thermal contraction cracks in permafrost. *J. Geophy. Res.* 102: 25,617-625,628.

Mellon MT, Arvidson RE, Marlow JJ, et al. (2008) Periglacial landforms at the Phoenix landing site and the northern plains of Mars. *J. Geophys. Res.* 113: doi:10.1029/2007JE003039.

Milliken RE, Mustard JF and Goldsby DL. (2003) Viscous flow features on the surface of Mars: Observation from high-resolution Mars Orbiter Camera (MOC) images. *J. Geophys. Res.* 108: doi:10.1029/2002JE002005.

Möhlmann DTF. (2010) Temporary liquid water in upper snow/ice sub-surfaces on Mars? . *Icarus* 207: 140-148.

Möhlmann DTF and Thomsen K. (2011) Properties of cryobrines on Mars. *Icarus* 212: 123-130.

Morgenstern A, Hauber E, Reiss D, et al. (2007) Deposition and degradation of a volatile-rich layer in Utopia Planitia, and implications for climate history on Mars. *J. Geophys. Res.* 112: doi:10.1029/2006JE002869.

Murchie S and the CRISM Science Team. (2007) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO). *J. Geophy. Res.* 112: doi:10.1029/2006JE002682.

Murton JB and Kolstrup E. (2003) Ice-wedge casts as indicators of paleotemperatures: precise proxy or wishful thinking? *Prog. Phys. Geog.* 27: 155-170.

Musselwhite DS, Swindle TD and Lunine J. (2001) Liquid CO_2 breakout and the formation of recent small channels on Mars. *Geophysical Research Letters* 28: 1283-1285.

Orloff TC, Kreslavsky M, Asphaug E, et al. (2011) Boulder movement at high northern latitudes of Mars. *J. Geophy. Res.* 115: doi:10.1029/2011JE003811

Orloff TC, Kreslavsky MA and Asphaug EI. (2012) Possible mechaism for boulder clustering on themal contraction polygons. *Lunar Plan. Sci. Conf. XLIII, Houston, Texas*: Abstr. 1652.

Owen T, Biemann K, Rushnek DR, et al. (1977) The composition of the atmosphere at the surface of Mars. *J. Geophy. Res.* 82.

Page DP. (2007) Recent low-latitude freeze–thaw on Mars. *Icarus* 189: 83-117.

Page DP and Murray JB. (2006) Stratigraphical and morphological evidence for pingo genesis in the Cerberus plains. *Icarus* 183: 46-54.

Pelletier JD, Kolb KJ, McEwen AS, et al. (2008) Recent bright gully deposits on Mars: Wet or dry flow? *Geology* 36: 211-214.

Pestova O, Myund L, Khripun M, et al. (2005) Polythermal Study of the Systems $M(ClO_4)_2$-H_2O (M^{2+} = Mg^{2+}, Ca^{2+}, Sr^{2+}, Ba^{2+}). *Russ. J. Appl. Chem.* 78: 409-413.

Plaut JJ, Safaeinili A, Holt JW, et al. (2009) Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars. *Geophys. Res. Let.* 36: doi:10.1029/2008GL036379.

Plescia JB. (1990) Recent flood lavas in the Elysium region of Mars. *Icarus* 88: 465-490.

Read PL and Lewis SR. (2004) *The Martian Climate Revisited: Atmosphere and Environment of a Desert Planet,* Berlin: Springer.

Reiss D, Erkeling G, Bauch KE, et al. (2010) Evidence for present day gully activity on the Russell crater dune field, Mars. *Geophys. Res. Let.* 37: doi: 10.1029/2009GL042192. .

Reiss D, Hauber E, Hiesinger H, et al. (2011) Terrestrial gullies and debris-flow tracks on Svalbard as planetary analogs for Mars. In: Barry WB and Bleacher JE (eds) *Analogs for Planetary Exploration: Geological Society of America Special Paper 483.* Geological Society of America, 567.

Reiss D, Hiesinger H, Hauber E, et al. (2009) Regional differences in gully occurrence on Mars: A comparison between the Hale and Bond craters. *Plan. Space Sci.* 57: 958-974.

Reiss D, van Gasselt S, Neukum G, et al. (2004) Absolute dune ages and implications for the time of formation of gullies in Nirgal Vallis, Mars. *J. Geophys. Res.* 109: doi:10.1029/2004JE002251.

Rossbacher LA and Judson S. (1981) Ground ice on Mars: Inventory, distribution, and resulting landforms. *Icarus* 45: 39-59.

Russell PS and Head JW. (2007) The Martian hydrologic system: Multiple recharge centers at large volcanic provinces and the contribution of snowmelt to outflow channel activity. *Plan. Space Sci.* 55: 315-332.

Ryan JR and Christensen P. (2012) Coils and Polygonal Crust in the Athabasca Valles Region, Mars, as Evidence for a Volcanic History. *Science* 336: 449-452.

Schorghofer N and Aharonson O. (2005) Stability and exchange of subsurface ice on Mars. *J. Geophys. Res.* 110: doi:10.1029/2004JE002350.

Seibert NM and Kargel JS. (2001) Small-scale martian polygonal terrain: Implications for liquid surface water. *Geophys. Res. Lett* 28: 899-902.

Séjourné A, Costard F, Gargani J, et al. (2011) Scalloped depressions and small-sized polygons in western Utopia Planitia, Mars: A new formation hypothesis. *Plan. Space Sci.* 59: 412-422.

Shean DE. (2010) Candidate ice-rich material within equatorial craters on Mars. *Geophys. Res. Let.* 37: doi:10.1029/2010GL045181

Snyder CW and Moroz VI. (1992) Spacecraft exploration of Mars. In: Kieffer HH, Jakosky BM, Snyder CW, et al. (eds) *Mars.* Tucson: University of Arizona Press.

Soare RJ, Burr DM and Wan Bun Tseung J-M. (2005) Possible pingos and a periglacial landscape in northwest Utopia Planitia. *Icarus* 174: 373-382.

Soare RJ, Kargel JS, Osinski GR, et al. (2007) Thermokarst processes and the origin of crater-rim gullies in Utopia and western Elysium Planitia. *Icarus* 191: 95-112.

Soare RJ, Osinski GR and Roehm CL. (2008) Thermokarst lakes and ponds on Mars in the very recent (late Amazonian) past. *Earth Planet. Sci. Lett* 272: 382-393.

Souness C, Hubbard B, Milliken RE, et al. (2012) An inventory and population-scale analysis of martian glacier-like forms. *Icarus* 217: 243-255.

Squyres SW. (1979) The distribution of lobate debris aprons and similar flows on Mars. *J. Geophy. Res.* 84: 8087-8096.

Squyres SW and Carr MH. (1986) Geomorphic evidence for the distribution of ground ice on Mars. *Science* 231: 249-252.

Tanaka KL, Chapman MG and Scott DH. (1992) Geologic map of the Elysium region of Mars. *U.S. Geol. Surv. Misc. Invest. Ser.*: MAP I-2147.

Treiman AH. (2003) Geologic settings of Martian gullies: implications for their origins. *J. Geophys. Res.* 108: doi:10.1029/1202JE001900.

Twidale CR. (1999) Landforms ancient and recent: the paradox. *Geogr. Ann. A* 81A: 431-441.

Ulrich M, Hauber E, Herzschuh U, et al. (2011) Polygon pattern geomorphometry on Svalbard (Norway) and western Utopia Planitia (Mars) using high-resolution stereo remote-sensing data. *Geomorphology* 134: 197-216.

Ulrich M, Morgenstern A, Günther F, et al. (2010) Thermokarst in Siberian ice-rich permafrost: Comparison to asymmetric scalloped depressions on Mars. *J. Geophy. Res.* 115: doi:10.1029/2010JE003640.

Vincendon M, Mustard J, Forget F, et al. (2010) Near-tropical subsurface ice on Mars. *Geophys. Res. Let.* 37: doi:10.1029/2009GL041426.

Williams KE, Toon OB, Heldmann JL, et al. (2009) Ancient melting of mid-latitude snowpacks on Mars as a water source for gullies. *Icarus* 200: 418-425.

Zanetti M, Hiesinger H, Reiss D, et al. (2010) Distribution and evolution of scalloped terrain in the southern hemisphere. *Icarus* 206: 691-706.

Zent AP, Hecht MH, Cobos DR, et al. (2010) Initial results from the thermal and electrical conductivity probe (TECP) on Phoenix. *J. Geophys. Res.* 115: doi:10.1029/2009JE003420, 002010.

Zurek RW and Smrekar SE. (2007) An overview of the Mars Reconnaissance Orbiter (MRO) science mission. *J. Geophy. Res.* 112: doi:10.1029/2006JE002701.

Figure/table captions for "Morphological evidence for geologically recent thaw of ice on Mars: case studies from very high resolution imaging data"

Figure 1. Dendritic valley networks in the cratered martian highlands, indicating a wetter climate in the ancient past. The formation of such fluvial valleys sharply declined between 3.8 Ga and 3.5 Ga at the end of the 'Noachian' epoch (HRSC false colour image of orbit h0532_0000; the large crater has a diameter of ~45 km and is centred at 12.43°S and 60.57°E). North is up in this and all other images unless otherwise stated or demonstrated by a north-arrow. Image credit ESA/DLR/FUB.

Figure 2. The martian obliquity cycle over the last 20 Ma. Obliquity changes by nearly 20° on an ~ 100 ka cycle (see inset). The magnitude of these obliquity changes vary on ~1 and ~2 Ma cycles. The mean obliquity changed from about 35° to about 25° at about 5 Ma, as shown by the dotted line (after Laskar et al., 2004). Prior to 20 Ma the obliquity is not well-constrained by models.

Figure 3. Examples of landforms on Mars that might have formed by thaw. a) martian hillslope gully at 38.58S, 319.88E (HiRISE image PSP_006888_1410). Note the alcove at the top of the slope, and the sinuous channels and debris fan at the foot of the slope. Illumination is from the left and north is up in this and all following Mars images unless otherwise specified. b) Gully and debris flow features on Earth (Hannaskogdalen, Svalbard) that are morphologically similar to the martian gullies. Svalbard image is an aerial photograph from the German DLR airborne 'HRSC-AX' camera (Hauber et al., 2011b). c-e) Time-series showing recurring slope lineae on the inner crater wall of Newton Crater near 41.6°S, 202.3°E. The lineae are the dark, finger-like structures that can be seen in d and e. Figure 3c shows the location before the lineae began. Dark arrows in d and e show the end points of the lineae, pale arrows indicate the position of these termini from the image before. The time series covers about 100 martian days ("sols") in total, and images d and e are separated by 35 sols. The lineae have therefore progressed at a rate of 1 m per day (HiRISE images PSP_0021555_1380; PSP_0022267_1380; PSP_0022689_1380). f) Lobate features on the inner wall of an impact crater on Mars near 71.98N, 344.58E (HiRISE PSP_010077_2520). g) Solifluction lobes on the slopes of Louisfjellet (Svalbard). Note the striking similarity in scale

and morphology between d) and e). Images a, b, d, and e are after Figures 3 and 6 in Hauber (2011a). Image credits: NASA/JPL/UofA and DLR.

Figure 4. Evidence for seasonal precipitation at martian mid-latitudes. A crater at 46.05°S and 183.85°E is shown at different seasons (seasons on Mars are indicated by solar longitude, L_S, with L_S=0 corresponding to the beginning of northern spring and a whole year being equivalent to 360°). Only pole-facing slopes in scenes acquired in southern winter (show bright deposits interpreted as water ice (cf. Vincendon et al., 2010). These locations correspond to places where periglacial-like features are preferentially observed. (a-c) HRSC false-colour views (image numbers: a-h2630_0001, b-h6547_0000, c-h8569_0000). (d-f) CTX images (image numbers: a-B11_013934_1337, b-P04_002779_1337, c-G03_019314_1337). Image credits NASA/JPL/UofA/MSSS

Figure 5. Examples of typical ice-related landforms in martian mid-latitudes. (a) Viscous flow features in Deuteronilus Mensae at the dichotomy boundary. The features indicate plastic deformation and resemble terrestrial glaciers. The perspective view towards North was generated from HRSC stereo scene h8289_0000 and is located at ~40°N and 23°E. (b) Small valleys downslope of viscous flow features (upper right; interpreted as rock glaciers). Arrows indicate inferred flow direction. Such valleys have been interpreted as glaciofluvial valleys formed by meltwater by Fassett et al. (2010) (detail of CTX image P04_002676_1413; centred at 38.24°S and 113.12°E). (c) Landforms typical of Utopia Planitia, Mars. Asymmetric scalloped depressions display steeper pole-facing slopes and cut large polygons that dissect the surrounding plains. Smaller polygons (see inset) overprint the depressions, indicating that landform evolution went on even after the degradation of the ice-rich substrate. Detail of HiRISE image PSP_001872_2260, centred near 45.6°N and 93.7°E. (d) Fractured mound that morphologically resembles pingos on Earth. The mound is located on a crater floor near 31.8°S and 347.2°E (detail of HiRISE image PSP_007533_1480). (e) Two scales of polygons on a crater floor near 64.5°N and 67.3°E (detail of HiRISE image PSP_008492_2450). Image credits NASA/JPL/UofA/MSSS and ESA/DLR/FUB

Figure 6. Assemblage of cold-climate features in a mid-latitude crater (detail of HiRISE image PSP_001684_1410; near 38.9°S and 196°E). a) Gullies (ravines) and associated fan deposits. b) Stripes oriented downslope. It is not possible to determine if the stripes are sorted

or not. c) Lobe-like features (arrows) indicative of downslope creep. Image credits NASA/JPL/UofA.

Figure 7. Sorted forms within and around Heimdal crater showing trends in morphology and clast abundance. The clastic areas appear cut by later fractures in all cases. Approximate slope measurements are given in bottom left corner of each panel. All images are lit from the lower left. (a) Clastic stripes on a steep slope on the inner crater wall of Heimdal crater. HiRISE image PSP_009580_2485. (b) Clastic polygons trending into clastic stripes on the outer crater wall. HiRISE image PSP_009079_2485. (c) Clastic rubble piles or 'islands' near the base of the inner crater wall. HiRISE image PSP_009778_2485. (d) Low-albedo polygons inferred to comprise sorted clasts below the image resolution. These polygons appear to be somewhat high-centred. HiRISE image PSP_009079_2485. Image credits NASA/JPL/UofA. After Figure 3 in Gallagher et al. (2011).

Figure 8. Landform assemblage on the inner walls of Heimdal crater. a). The upper part of the image shows the crater rim, and the lower part the crater interior. Lobate, clastic forms (b and blockfields (c) can be seen. Blockfields near the crater rim trend into linear and lobate forms (downslope of the blockfield in c), and linear slope-parallel forms (throughout the centre of the image; see also Figure 7a), are all visible and in b) trend into lobate forms. Nearer the base of the inner crater wall the slope is less and the surface appears rougher, perhaps pitted in places, and contains fewer organised clastic landforms. Part of HiRISE image PSP_009778_2438. Image credits NASA/JPL/UofA.

Figure 9. a) Stone banked lobes incised by gullies on the interior slopes of a crater at ~ 59.5° N 302.4° E; boxes show relative locations of Figs. 9b, d and e. Lobes are characterised by bright treads and dark, clastic risers. In places, lobe assemblages give way to polygonally fractured ground of more uniform tone (P), although subtle albedo variation suggests that this ground may be the reworked continuation of the adjacent lobes. Gully-fan systems (Q) have incised many of the lobes, wiping-out some completely while only partially deflating others. b) Lobes exhibiting bright, fine textured low angle treads bounded by dark, steeper clastic risers; box shows relative location of Fig. 9c. c) Clastic lobes are fed by slope-parallel clastic stripes. Interlobate surfaces show a more pronounced fracture pattern (visible also in Fig. 9b more broadly), suggesting that the lobes here are accumulations overlying fractured ground. d) Lobe deflation by a gully rill with a small distal, fan-like, sediment accumulation (X). The

next clastic riser downslope (Y) has been deflated by branching gully rills, demonstrating that solifluction was succeeded by liquid flow across the surface. e) Axial gully and rills have incised a texturally fine tread (A) but only partly deflated the clastic riser (B). The sudden introduction of these eroded and winnowed sediments probably caused the transport capacity of the gully system to be exceeded where the gradient of the gully diminished on the next tread downslope, triggering deposition of the fan on this surface (C). Parts of HiRISE image PSP_007666_2400. Image credit NASA/JPL/UofA. After Fig 14 in Gallagher et al. (2011) Figure 14.

Figure 10. Planview images showing the Athabasca Vallis source area. a) Context view showing segments of the Cerberus Fossae fracture system (A), the apparent twin source regions (C, D) of Athabasca Vallis, and the extent of Figure 10b (marked by the white box). The darker toned surfaces match the mapped extents of the channel floor. The white arrow indicates the direction of flow; Athabasca Vallis extends for ~ 250 km in this direction. Part of HRSC nadir image h1196. b) Higher resolution view of a part of the western source region. White boxes labelled P, Q, R show the locations of Figures 12, 11, and 13 respectively. Mosaic of HiRISE images PSP_007843_1905 and PSP_009280_1905. Image credit NASA/JPL/UofA and ESA/DLR/FUB. After Balme and Gallagher (2009).

Figure 11. Scarps at the margin of a low-relief, polygonally patterned surface (P). The scarps contain multiple small amphitheatre-shaped niches containing smooth material (Q),and are fronted by accumulations of meter scale clasts (R), and contributory channel networks (S). Note the “spurs” protruding from the sides of the niches. The channels appear incised into a faintly polygonised surface and terminate in a hummocky deposit in a low basin (T). There is a possibly leveed flow-like feature (arrowed) within the channel terminal deposits. Part of HiRISE image PSP_009280_1905. Image credit NASA/JPL/UofA. After Balme and Gallagher (2009).

Figure 12. Niche-indented scarps surrounding linked basins. Here, the topographically highest polygonised surfaces (A) appear to have degraded to form shallow basins. The shallowest depressions have polygonised floors, as do the outer floors of deeper depressions (B). Several of the larger basins have roughly textured floors, sometimes containing mound/cone landforms (C). The small image, lower right, shows a higher resolution view of one of these basins (in the white box) and reveals cone-like landforms (X) and incised gullies

on the slopes of the basin beneath the headscarp. Small gullies are also seen at Y. A single outflow channel from a shallow, polygonised depression is shown at Z, and could be a "tapping" channel via which fluid drained the depression. The topographically lowest part of the scene (D) has a more subdued texture than the other polygonised surfaces. Part of HiRISE image PSP_007843_1905. Image credit NASA/JPL/UofA. After Balme and Gallagher (2009).

Figure 13. Shallow, composite basin within the main Athabasca Vallis channel. The basin appears to have formed by the merging of other small basins that grew in the polygonally patterned ground (A), as shown by the causeways and remnant headlands (B) of polygonised material. It is clear that development of individual basins was accompanied within by the formation of moated, conical landforms, strengthening the interpretation of these forms as pingos. At the west, scarp-parallel ridges beneath the headscarp (X) appear similar to terrestrial subsidence failures. A prominent channel enters the basin to the north at Y. The floor of the basin is dominated by cone/mound landforms. Part of HiRISE image PSP_009280_1905. Image credit NASA/JPL/UofA. After Balme and Gallagher (2009).

Table 1. Possible periglacial landforms on Mars.

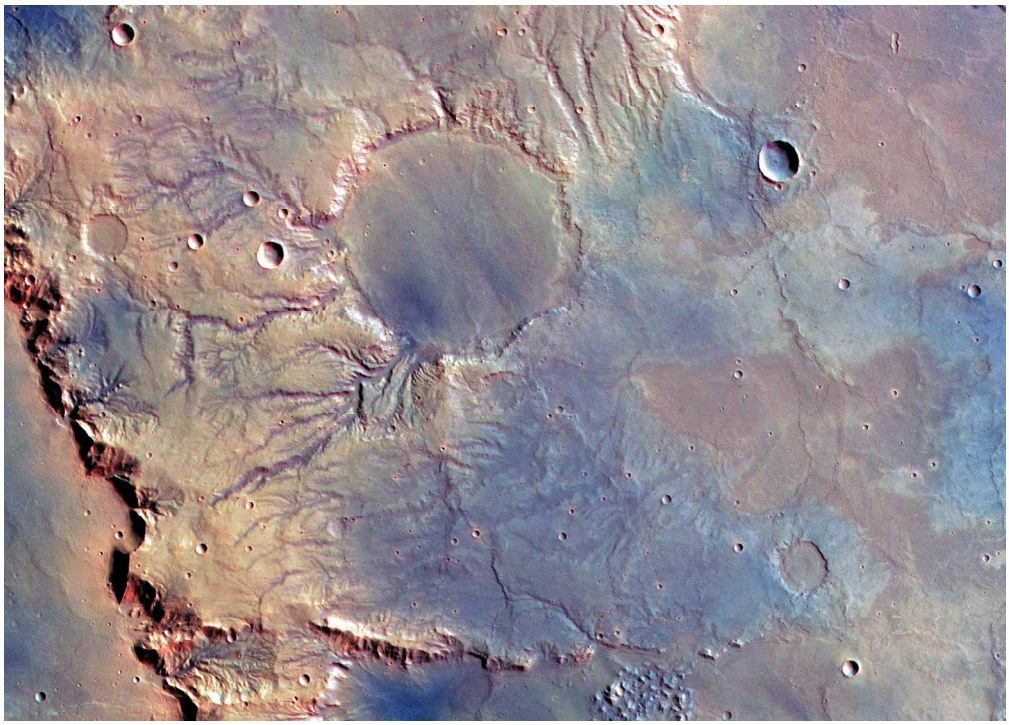


Figure 1
150x107mm (300 x 300 DPI)

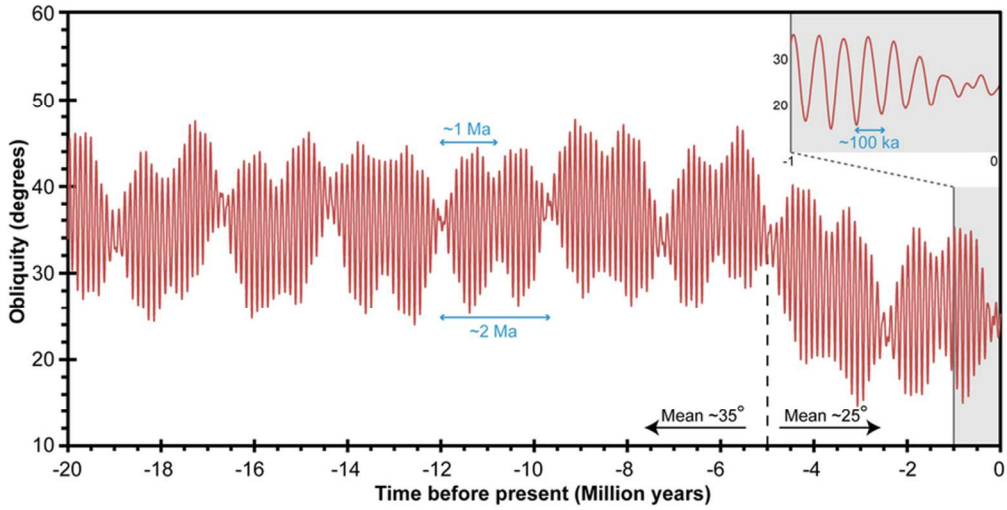
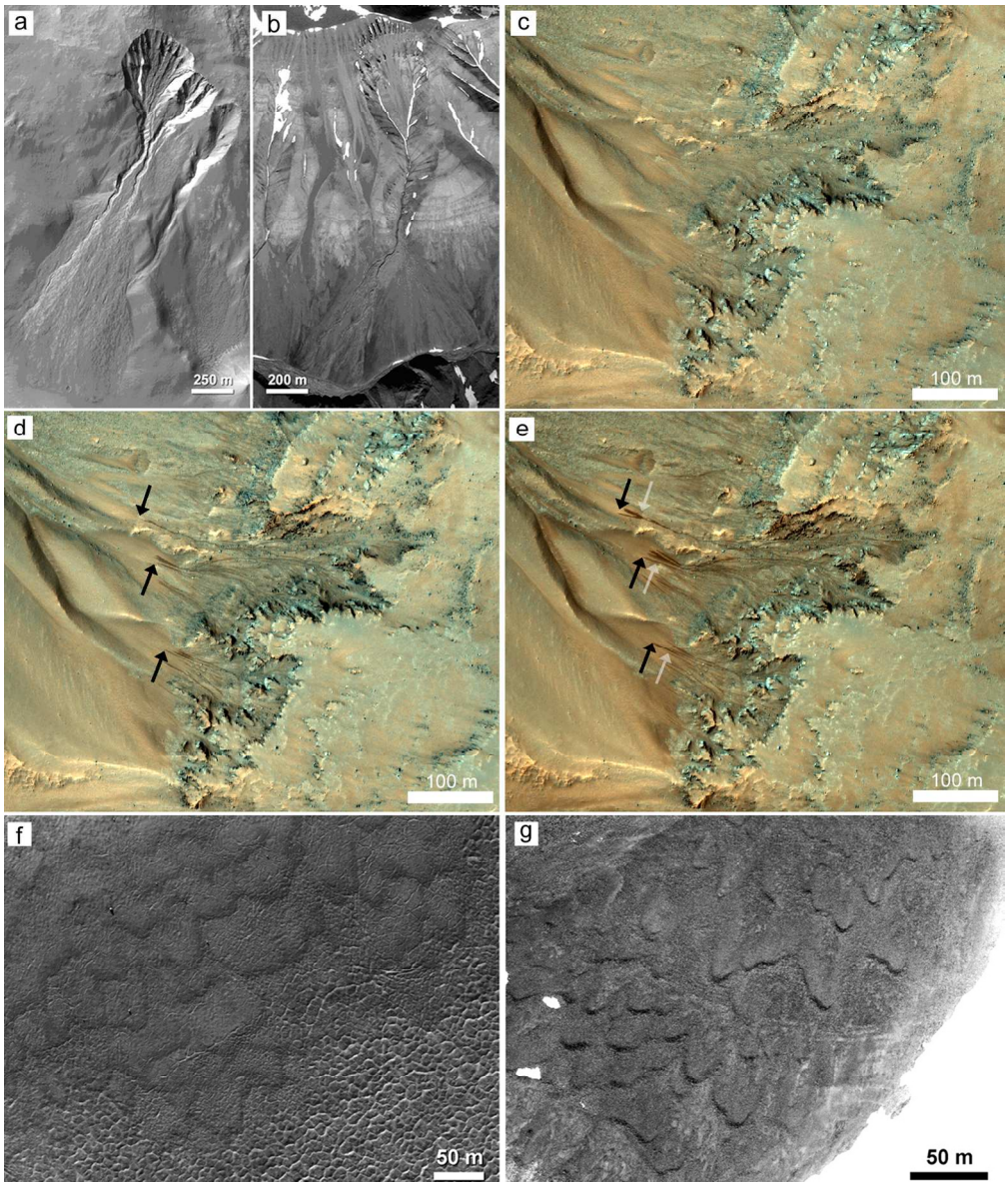


Figure 2
75x38mm (300 x 300 DPI)



149x175mm (300 x 300 DPI)

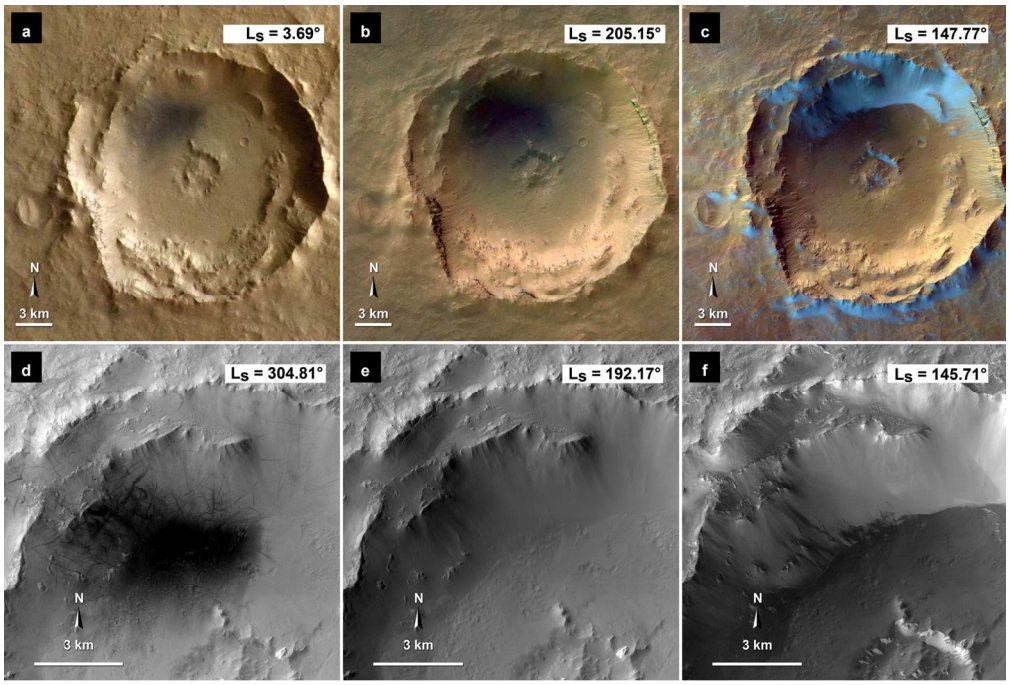


Figure 4
150x101mm (300 x 300 DPI)

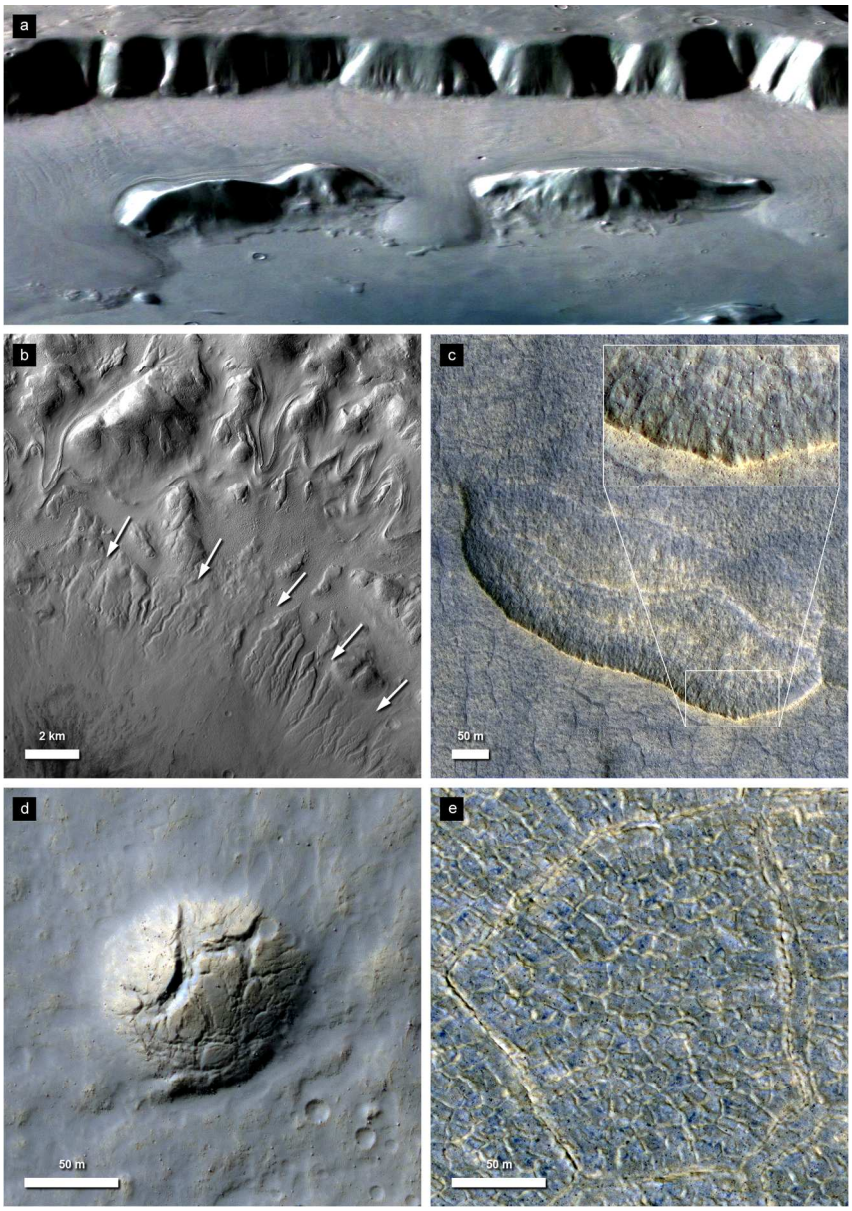


Figure 5
150x213mm (300 x 300 DPI)

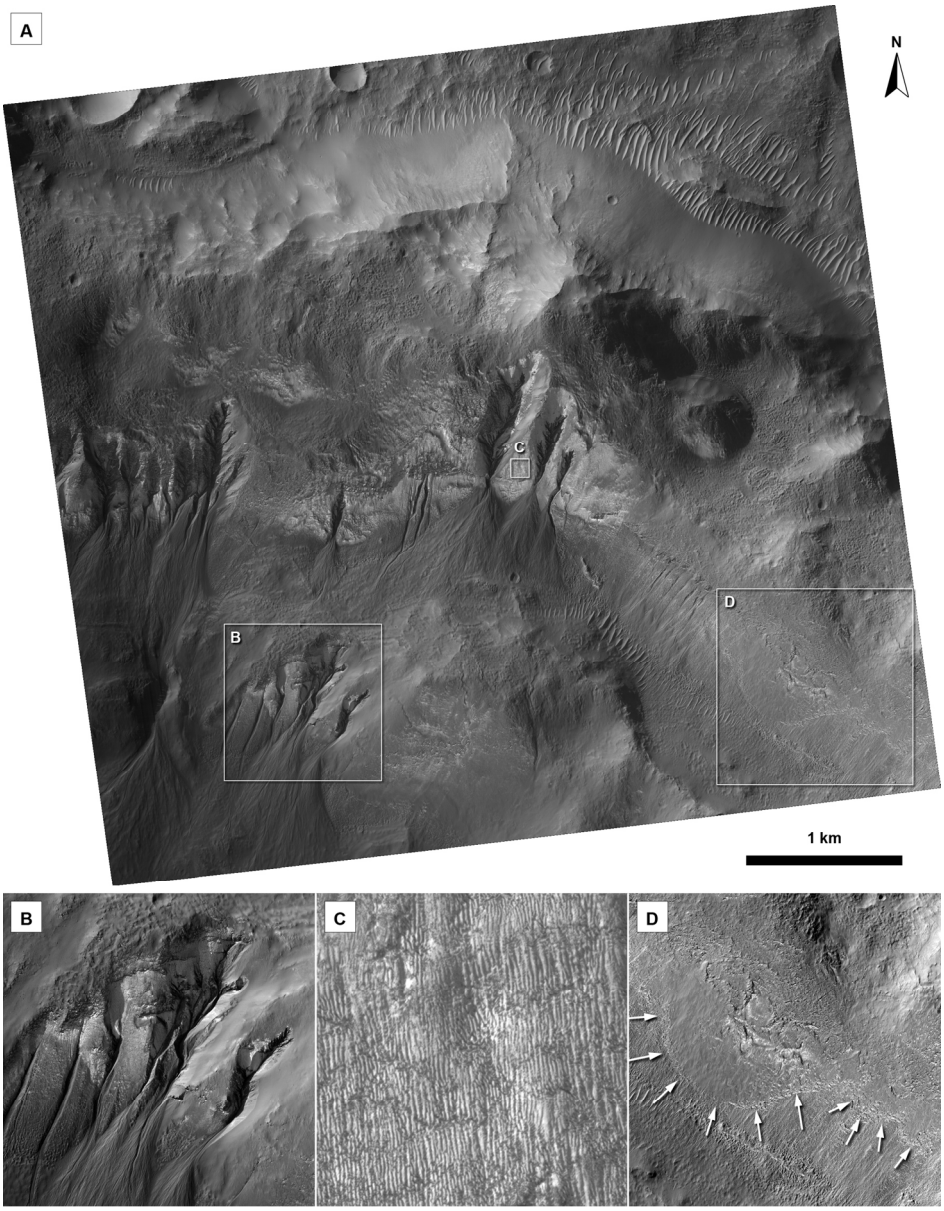


Figure 6
150x191mm (300 x 300 DPI)

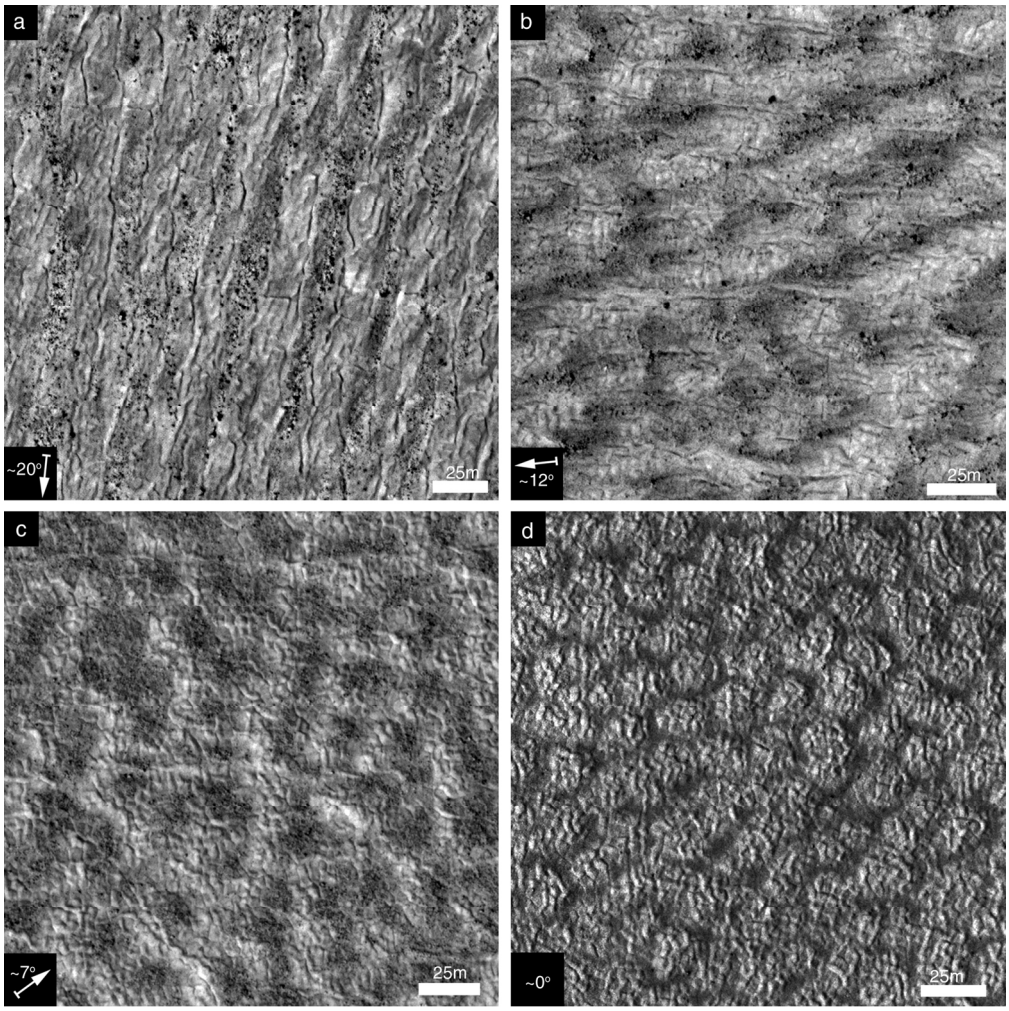


Figure 7
150x150mm (300 x 300 DPI)

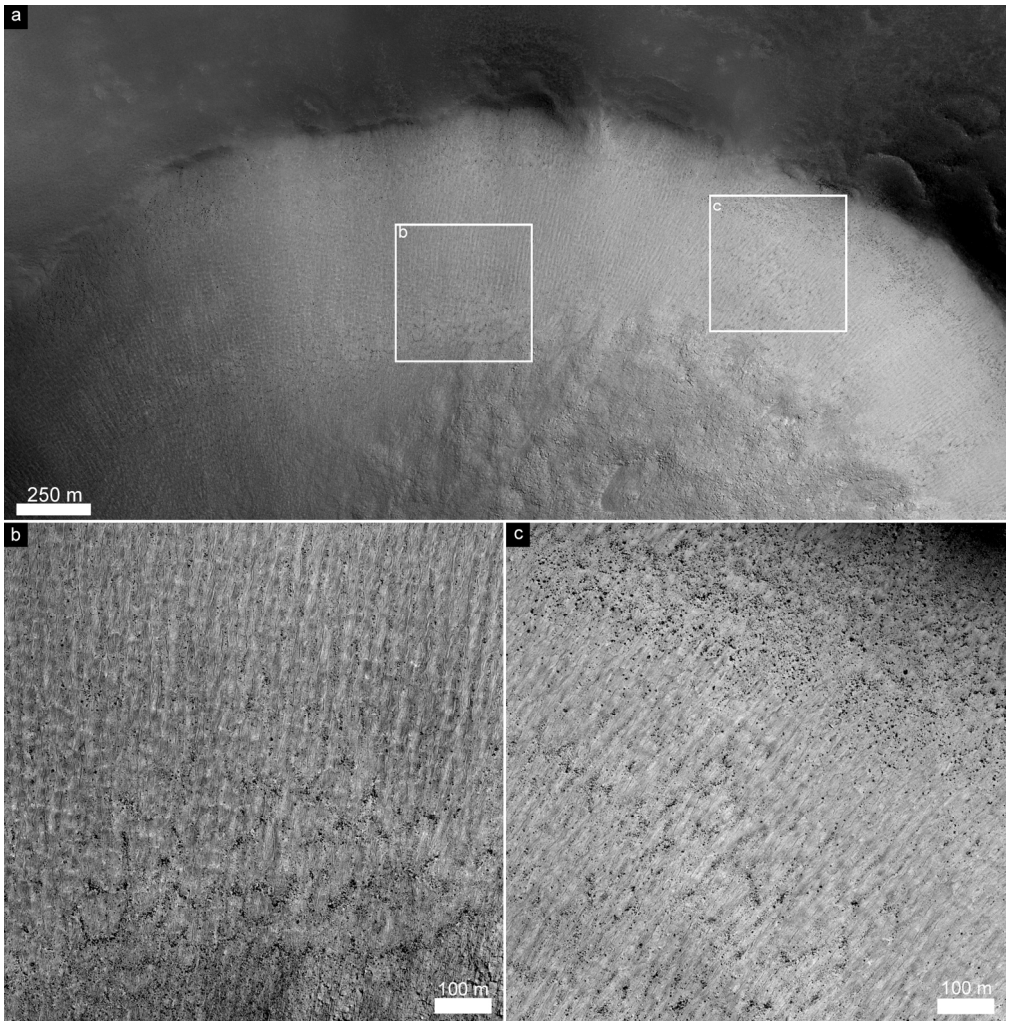


Figure 8
152x155mm (300 x 300 DPI)

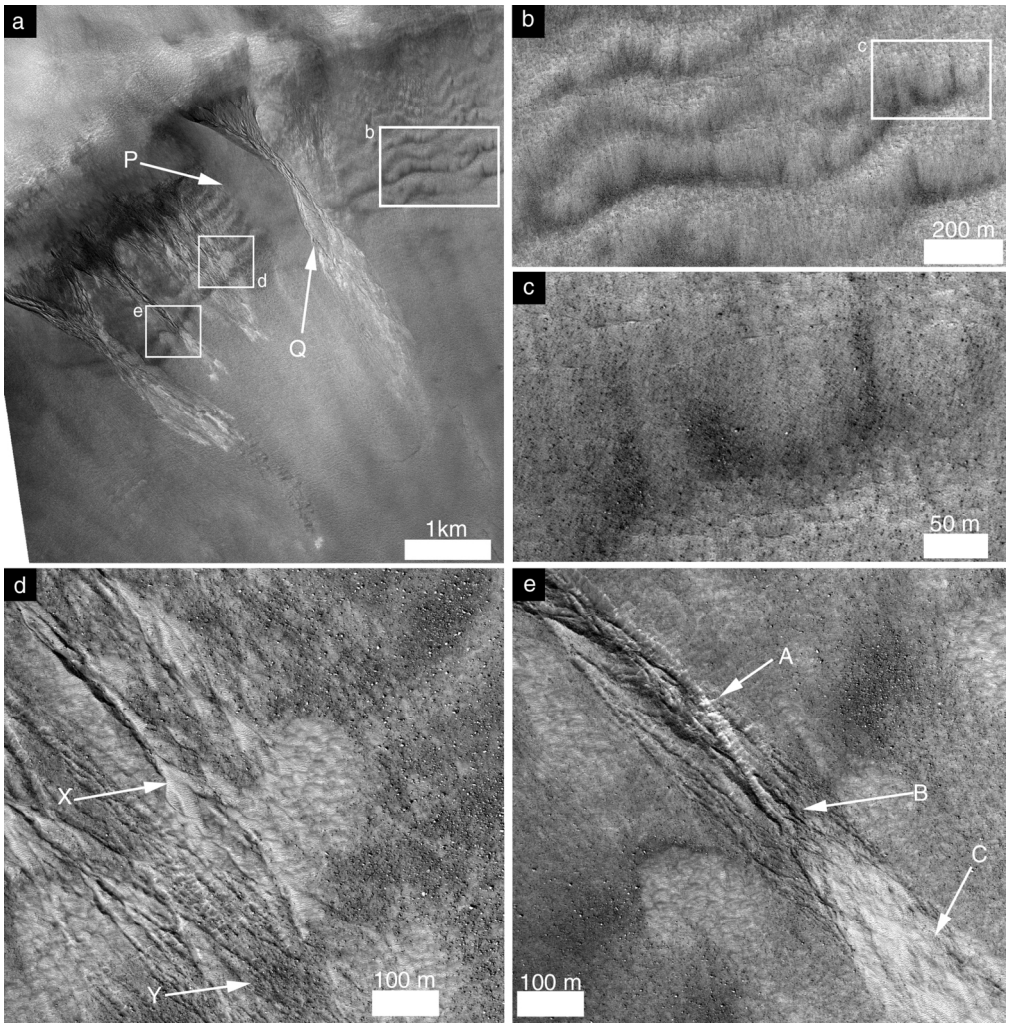


Figure 9
158x161mm (300 x 300 DPI)

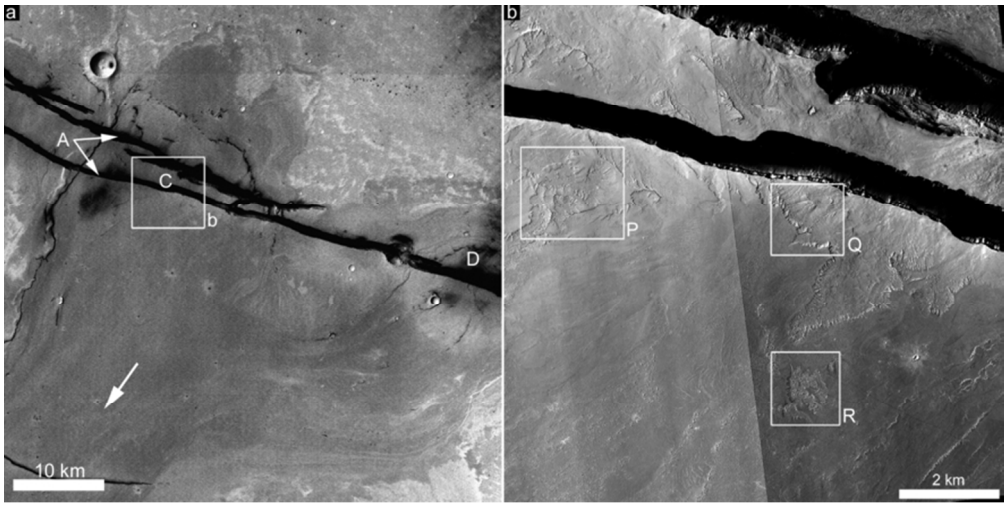


Figure 10
74x37mm (300 x 300 DPI)

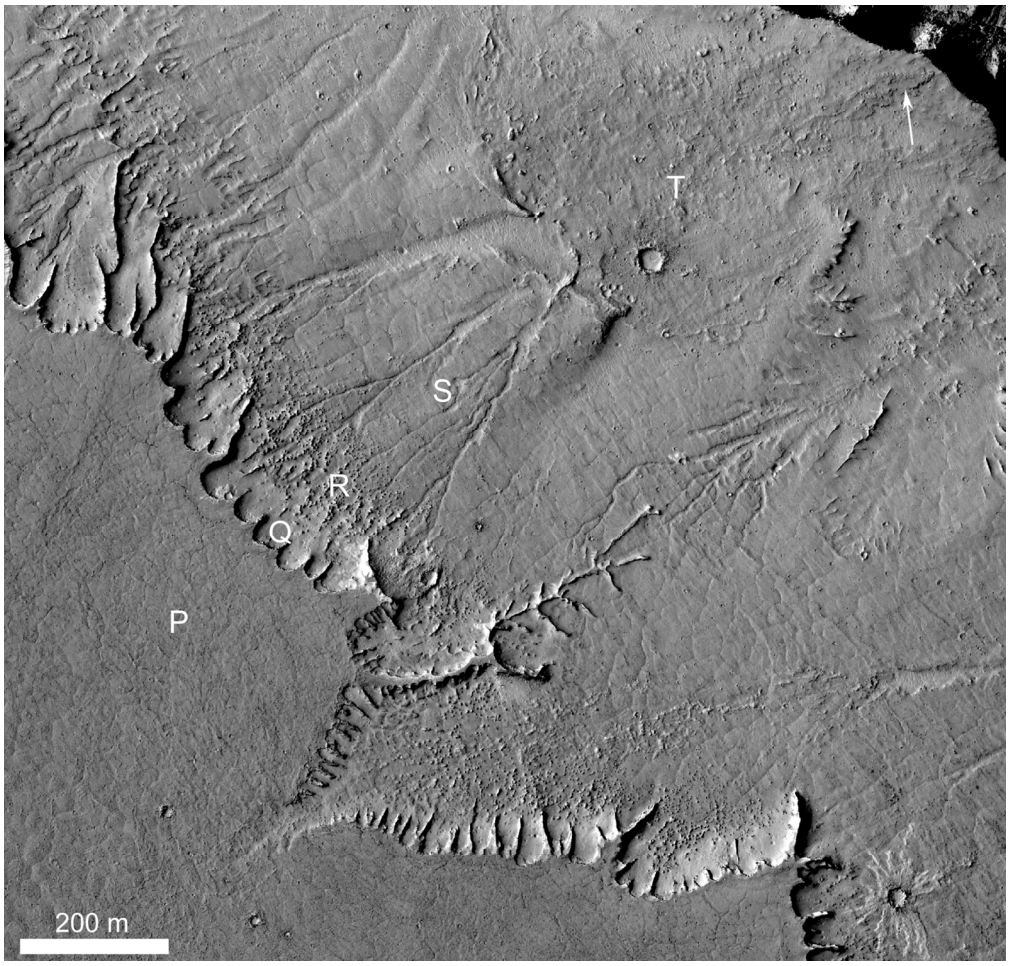


Figure 11
152x145mm (300 x 300 DPI)

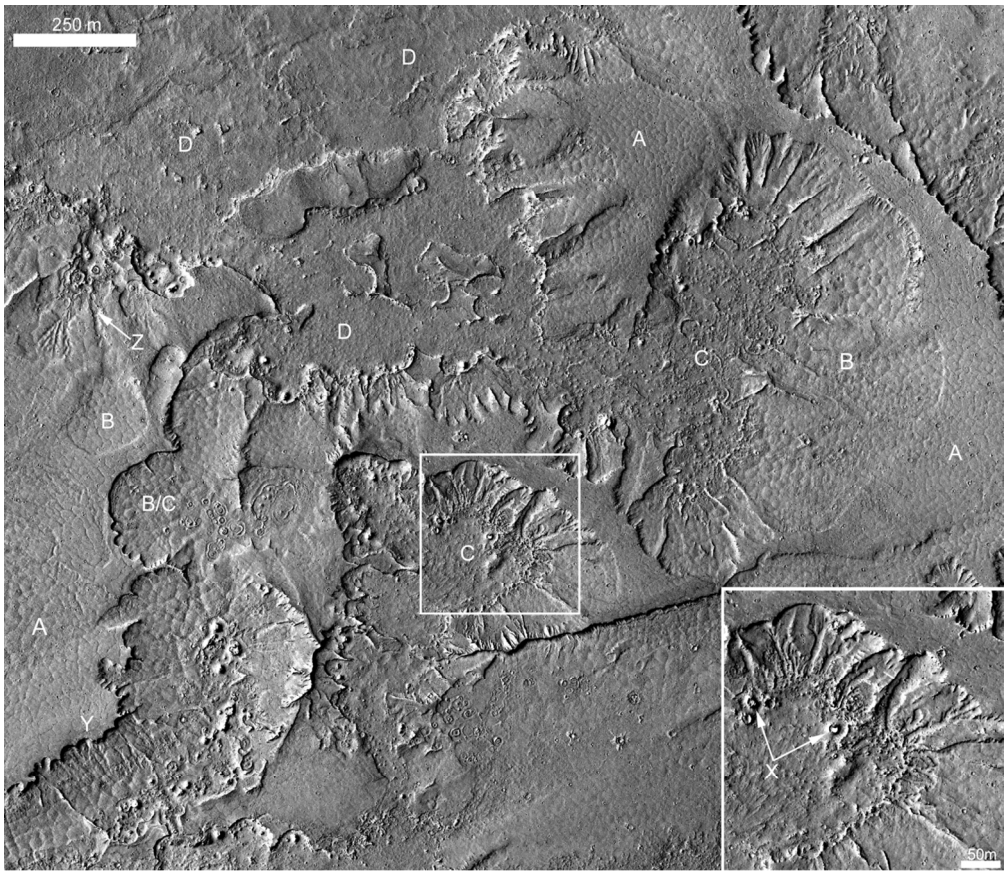


Figure 12
129x111mm (300 x 300 DPI)

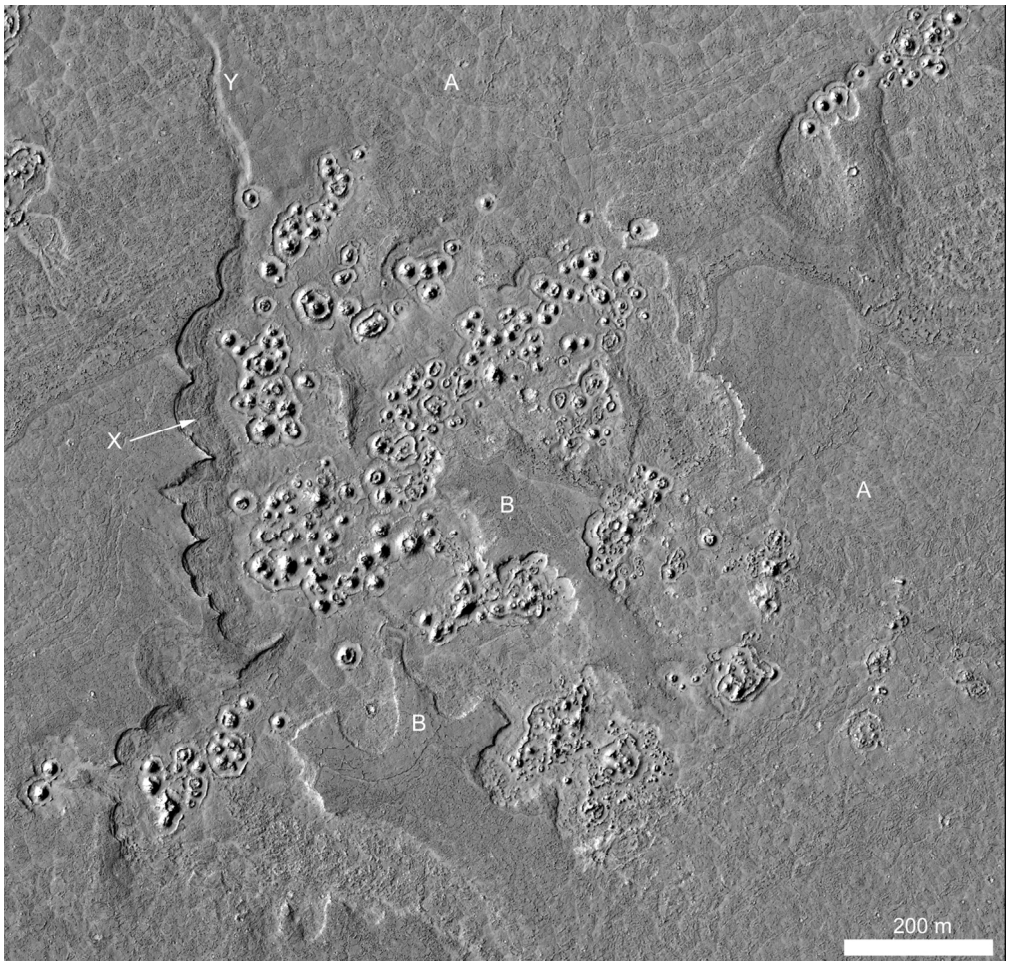


Figure 13
143x136mm (300 x 300 DPI)

Landform (morphology)	Periglacial interpretation	Indicative of liquid water?	Selected references	Alternative, dry interpretation	Alternative, dry interpretation References
Polygonally patterned ground	Thermal contraction polygons: (1) ice-wedge polygons (2) sand-wedge polygons (3) sublimation polygons	 (1) yes (2) no (3) no	 (1) (Seibert and Kargel, 2001) (2,3) (Levy et al., 2009a; Levy et al., 2010)	Desiccation cracks	(El Maarry et al., 2010)
Alternating dark and bright stripes	Sorted and unsorted stripes	yes (?)	(Hauber et al., 2011a; Hauber et al., 2011b; Mangold, 2005)	N/A	N/A
Clastic stripes	Sorted stripes	yes	(Gallagher and Balme, 2011; Gallagher et al., 2011)	N/A	N/A
Clastic circles, labyrinths and "rubble piles"	Sorted patterned ground	yes	(Balme et al., 2009; Gallagher and Balme, 2011; Gallagher et al., 2011)	Gravity-sorted clastic patterned ground enhanced by sublimation	(Heet et al., 2009; Levy et al., 2009a; Mellon et al., 2008)
Clastic lobes	Solifluction lobes	yes	(Gallagher and Balme, 2011; Gallagher et al., 2011; Johnsson et al., 2011)	N/A	N/A
Viscous flow features	Rockglaciers, or Debris-covered glaciers	no	(Head et al., 2010; Squyres, 1978; Squyres, 1979)	Aeolian deposits	(Zimbelman et al., 1989)
Small-scale valleys	Supra- and proglacial valleys	yes	(Dickson et al., 2009; Fassett et al., 2010)	N/A	N/A
Scalloped depressions	Thermokarst (melt)	yes	(Soare et al., 2007; Soare et al., 2008)	'Cryokarst' (Sublimation)	(Lefort et al., 2009; Morgenstern et al., 2007; Ulrich et al., 2010)
Mounds with pitted or fractured top	Pingos	yes	(Burr et al., 2009; Dundas et al., 2008; Page and Murray, 2006; Soare et al., 2005)	(1) Erosional remnants (2) Volcanic "rootless cones"	(1) (e.g., Burr et al., 2009; Dundas and McEwen, 2010) (2) (e.g., Jaeger et al., 2007; Lanagan et al., 2001)
Gullies	Erosion by fluvial or debris flow processes	yes	(Malin and Edgett, 2000); (Costard et al., 2002)	Dry mass wasting CO_2 erosion	(Bart, 2007; Treiman, 2003) (Musselwhite et al., 2001)
Recurring slope lineae	Seepage of thaw liquid from buried deposits	yes	(McEwen et al., 2011)	N/A	N/A

Table 1.